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OPTIMIZATION OF EQUIPMENT AND TECHNIQUES FOR WELDING ALUMINUM IN THE THICKNESS RANGE OF ABOUT 1/16 TO 1/4 INCH

Richard K. Sager, et al

Aluminum Company of America

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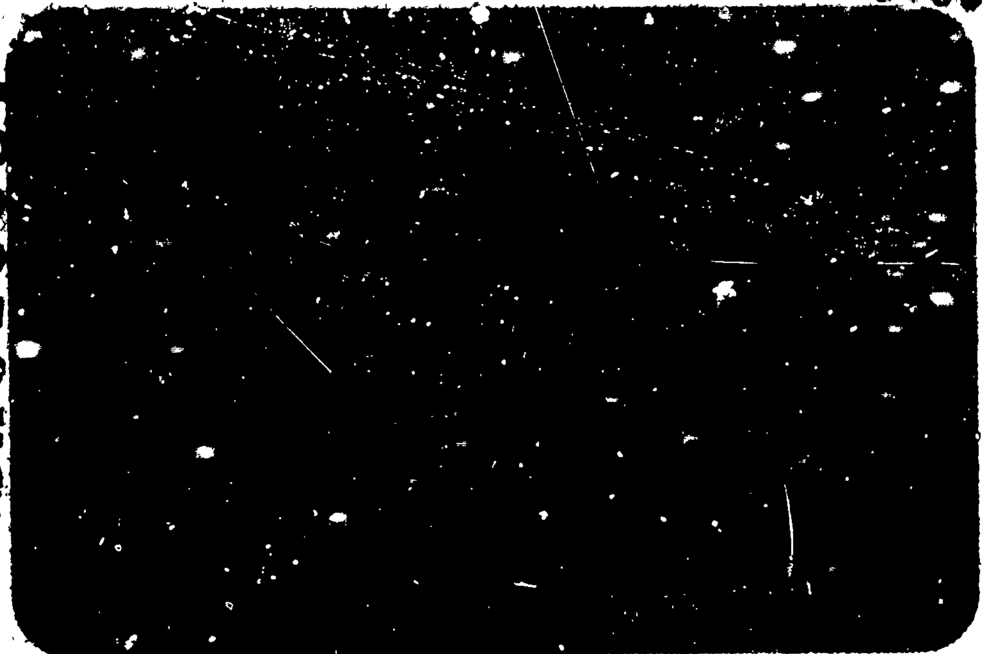

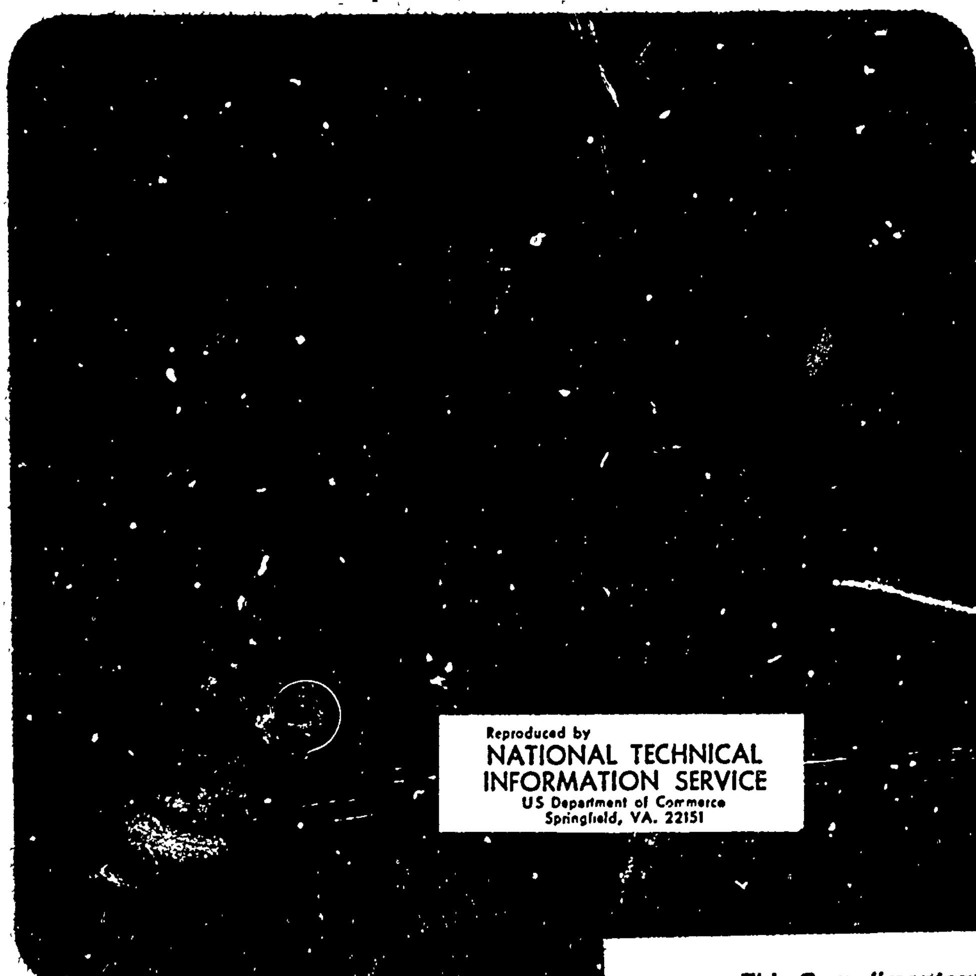

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The welding of thin gauge aluminum marine structures in the past has caused considerable problem mainly due to distortion in the fabricated structure and problems of meeting weld quality standards. The laboratory phase of this contract fabricated fillet welded panels, using GMAW, pulsed GMAW, high-frequency resistance welding, explosion welding, and electron beam weldtrusion (in-chamber). Butt weld investigations included conventional GMAW, plasma GMAW, and sliding seal electron beam (out of chamber).

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OPTIMIZATION OF EQUIPMENT AND TECHNIQUES FOR WELDING ALUMINUM IN THE THICKNESS RANGE OF ABOUT 1/16 TO 1/4 INCH

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FINAL REPORT

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Program Manager
July 28, 1975

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FOREWORD

This was prepared by the Aluminum Company of America under Contract N00024-74-C-5502 issued by the Naval Ship Systems Command. Technical Supervisor for this contract was NAVSEC Code 6101D.

The authors are indebted to Mr. F. Rudolph for conducting the ultrasonic fillet weld penetration analysis reported in the appendix. The cooperation and the assistance of Rohr Industries in gaining butt welded panels; the plasma GMAW from Phillips Corporation, Netherlands, and the sliding seal electron beam welds from Sciaky, France; Babcock and Wilcox Research Division for supplying the in-chamber electron beam weldtrusion panels and Battelle Columbus Laboratory for supplying the explosion and high-frequency resistance welded panels, is greatly appreciated.

ABSTRACT

The welding of thin gauge aluminum marine structures in the past has caused considerable problem mainly due to distortion in the fabricated structure and problems of meeting weld quality standards. The laboratory phase of this contract fabricated fillet welded panels, using GMAW, pulsed GMAW, high-frequency resistance welding, explosion welding, and electron beam weld-trusion (in-chamber). Butt weld investigations included conventional GMAW, plasma GMAW, and sliding seal electron beam (out of chamber). For conventional GMAW welding, power sources, shielding gas mixtures, and travel speeds were evaluated for their effect on panel distortion, joint soundness and strength. All of the specimens were evaluated for static and fatigue strength, corrosion fatigue, corrosion resistance, hardness, residual stress, shrinkage, heat input, and distortion. The contract analyzes the results of fabrication and evaluation of the fabricated specimens, along with equipment costs and economics to attempt to determine the optimum weld process for various types of ship construction. The report finds that conventional GMA welding still combines the best combination of low-cost equipment and sound weld joint integrity, thus making it the optimum welding process for fillet and butt welding for aluminum ship construction. The sliding seal electron beam equipment used to produce butt welds is extremely close to conventional GMAW welding in the total evaluation and is superior in weld joint performance. In addition to welding, the contract attempted to develop an ultrasonic non-destructive test to determine the amount of penetration in a fillet welded joint. This work is thoroughly reported in the report's appendix.

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Section 1 - Introduction

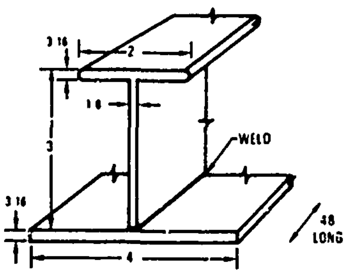
1.1 General - The laboratory investigations for welding thin gauge aluminum structures completed in this contract were in accordance with the initial proposal written by Alcoa, December 11, 1973, in response to Naval Ship Systems Command Solicitation No. N00024-74-R-7177(S). This contract was envisioned as a potential major building block on which additional studies would be made involving the various technologies necessary to design and construct, economically, large, complex aluminum structures for advanced marine vehicles. Since this contract was awarded, additional welding and fabrication work on aluminum has been undertaken in NAVSEA Contract N00024-74-C-0924, using a good deal of the preliminary work done in this contract as a start.

The results of this investigation are an attempt to compare many different types of welding processes to be used on advanced marine aluminum structures.

The program did not allow for the development of optimum joint configurations for each process. In explosion and high-frequency resistance welding, the joints selected were not advantageous to the particular welding processes, resulting in less than expected strength properties or fabrication difficulties. Our final analysis of these welding processes, however, takes into account these initial problems and projects the use of these processes utilizing an optimum joint configuration. In addition to comparing welding processes, the large volume of data generated on 5456 aluminum structures is a significant contribution to understanding aluminum weldments in marine applications. Hopefully, this will add to basic structural data on 5456 available to designers of advanced marine vehicles.

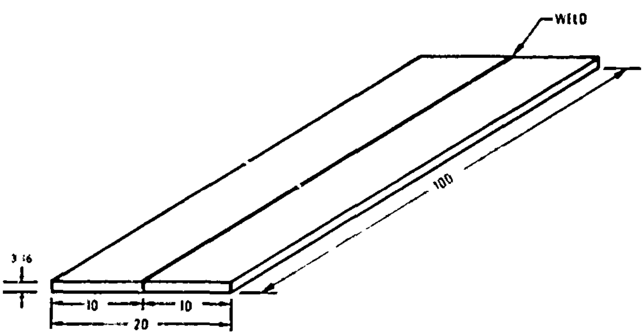
1.2 Objective - The objective of this contract was to determine the optimum welding process for welding thin gauge aluminum structures. The determination of the optimum welding process is based on joint integrity and strength, shrinkage and distortion, corrosion resistance, welding speed, capital investment, and auxiliary facilities necessary in order for welding to take place. The contract evaluates both fillet welds for shop fabrication and butt welds for in-shipyard or field erection fabrication.

1.3 Materials and Specimen Geometry - The alloy and structural shape selection is critical to the applicability of the data generated in this contract to shipyard fabrication of advanced marine vehicles. Aluminum alloy 5456 was selected for evaluation since it is the highest strength aluminum-magnesium weldable structural alloy commercially available today. 5456 has been used for most advanced marine vehicles constructed to this point. In addition, advanced hydrofoils and large surface effect ship preliminary designs specify 5456 for their main structural components. The structural section for the fillet welding examination, described in Figure 1-1, was used because it represents typical stiffened panel construction being specified on advanced marine vehicles today. Alcoa feels that the 3/16" sheet utilized is near the minimum that will be specified on future large advanced marine vehicles. The butt weld specimen, tested in this contract, is depicted in Figure 1-2.



TEE STIFFENER TO SHEET SPECIMEN

FIGURE 1-1



BUTT WELDED PANEL

FIGURE 1-2

1.4 Report Organization - Section 2-Fabricating Procedures will provide details on equipment, fixturing and welding parameters used for the five fillet welding processes and three butt welding processes evaluated. Some initial screening test data, especially on distortion, will be presented in Section 2; however, the final stiffened panel (Fig. 1-1) distortion measurements for all processes will be in Section 4. Section 3-Evaluation Procedures outlines the final testing procedures used to evaluate each welding process. Section 4-Results of Evaluation presents the data generated from final evaluation of the fillet and butt weld processes. Section 5-Analysis of Results analyzes all of the information collected while fabricating and evaluating the panels, in order to begin to compare the various processes. Economic information generated by the contract or supplied to Alcoa by the subcontractors also is included in Section 5. Section 6-Conclusions ranks the total performance of the weld processes and points out areas of superior or inferior performance by the welded joint. Section 7-Recommendations lists Alcoa's recommendations for the future use of the weld processes evaluated and what research and development efforts may be necessary in order to improve some of the processes.

In order to make many of the analyses and comparisons necessary to attempt to determine the optimum process for ship fabrication, the environment to which these processes will be exposed must be defined. Alcoa engineers agreed that the most likely environment would be the construction of a large all-aluminum high performance ship using two different types of construction:

1. Panel shop construction of large panels (as large as 8 ft. x 40 ft.) with longitudinal "T" stiffeners welded on at a spacing of from 8" to 18".

2. In-shipyard or field erection fabrication where large panels, sub-assemblies, and miscellaneous structurals will be joined to the ship.

In both cases fillet and butt welds will be necessary. The reader should keep this base in mind when reading the material in Sections 5 and 6.

Section 2 - Fabrication Procedure

Butt welded panels and fillet welded "T" stiffened panels were fabricated to determine the effects of the welding processes on distortion and performance. Other factors such as welding speed, capital investment and additional facilities were also reviewed.

A total of five (5) different fillet welding processes and three (3) different butt welding processes were evaluated. Fillet welded panels as shown in Figure 2-1 were fabricated using 5456-H111 "T" extrusions and 3/16" thick 5456-H116 sheet material. The five fillet weld processes were:

1. Conventional GMAW (MIG)
2. Pulsed GMAW (MIG)
3. High Frequency Resistance
4. Explosion Welding
5. In Chamber Electron Beam Weldtrusion

In addition, butt welded panels as shown in Figure 2-2 were fabricated using 3/16" thick 5456-H116 sheet material. The butt welding processes evaluated were:

1. Sliding Seal Electron Beam
2. Conventional GMAW (MIG)
3. Plasma GMAW

2.1 Fabrication of "T" Stiffened Panels - All sheet material was received in 240" x 96" size and either saw cut or machined to panel dimension. The "T" extrusion material was received in 20' lengths and was saw cut to the required lengths. Surface cleaning preparation used for each process is described in the subsections. The heat input for each of the joining processes is listed in Table 2-1.

2.1.1 Conventional GMA Welding (MIG) - Procedures were established to apply 1/8" fillet welds between the 1/8" thick leg of the "T" extrusion and 3/16" sheet with a minimal amount of distortion. This phase of development included: the determination of the proper arc current, voltage and travel speed; comparison of constant voltage, constant current and constant energy (drooping volt-ampere characteristic) power supplies; evaluation of argon and/or helium gas shielding mixtures; the determination of the best starting and controlling characteristics for uniform results; and the effect of restraint or predistortion of panels in improving weld flatness.

Since the purpose of the initial screening program was to determine the best gas mixture and power supply slope, all distortion measurements, bend tests, and macrostructure results are listed in this section. All screening samples were fabricated without predistortion. Initial procedure specimens were welded using only single fillet welds which were evaluated by macrosections and bend-fracture tests to determine weld soundness and fillet size. When optimum parameters were developed to produce a 1/8" fillet size with proper penetration and soundness, double fillet welded panels were fabricated. A total of twenty (20) final "T" stiffened panels were fabricated using the dual torch setup and predistortion fixture. Predistortion was used on the final panels to determine how consistently a flat panel could be fabricated.

Two (2) additional "T" stiffened panels were fabricated with optimum parameters and without predistortion. These panels were fabricated to compare with panels fabricated by the other weld processes that did not receive predistortion.

2.1.1.1 Equipment and Fixture - The single fillet weld panels were fabricated in the weld fixture shown in Figure 2-3. This fixture positioned the "T' extrusion in the center of the sheet and held it so twisting would not occur; however, the 3/16" sheet was allowed to move. No tack welding was employed. The welding equipment used in this phase of the program is listed below:

1. Linde SEH-3 Wire Feed Head
2. Linde HW-13 Torch
3. Linde SCC-1 Control
4. Linde OM-48 Side Beam Travel Carriage Unit with Linde Type "C" Electronic Governor

Preliminary samples were welded using the Westinghouse 500 amp constant energy (drooping volt-ampere characteristic) D.C. rectifier power supply. However, after a few weld tests, the power supply was changed to the Tek-Tran 1,000 ampere continuously variable slope D.C. rectifier power supply. This change was made to allow evaluation of the full range of power supply volt-ampere characteristics ranging from the constant current slope to the constant voltage slope utilizing the same electronic components in this multiple slope power supply.

2.1.1.2 Basic GMA Parameter Determination - The initial fillet welds were fabricated by automatic GMA fillet welding a vertical 1/8" thick 5456-H116 sheet to a horizontal 3/16" thick 5456-H116 sheet. Welding parameters were adjusted to achieve a 1/8" fillet size by using high heat input to break up the oxide layer and drive the arc to get proper penetration. Both 1/16" and 3/64" diameter 5556 electrode were employed in the weld evaluation. However, even welding at 80 ipm, the 1/16" diameter electrode produced a molten area that was too large to result in a 1/8" fillet size. The 1/8" fillet, with good penetration, could be made when employing 3/64" diameter 5556 electrode. Consequently, the remaining sections of the welding program used 3/64" diameter 5556 electrode.

A typical example of a 48" long panel with a 1/8" fillet weld can be seen in Figure 2-4. After welding was complete, a macrosection of each end of the specimen was prepared to ascertain the desired depth of penetration and fillet size. A bend test was also employed in order to examine the fractured surface for uniformity of penetration and weld soundness.

The basic weld parameters developed were:

Current - 200 amperes reverse polarity D.C.
Arc Voltage - 20 volts
Travel Speed - 80 ipm
Gas Flow - 60 cfh (30 He + 30 Ar)
Electrode Diameter - 3/64"

2.1.1.3 Evaluation of Power Supplies and Shielding Gas Characteristics - Using the Tek-Tran continuously variable slope D.C. rectifier power supply, the following volt-ampere characteristics were evaluated:

1. Constant Current (90% Slope Setting on Power Supply)
2. Constant Voltage (0% Slope)
3. Constant Energy Drooping Volt-Ampere (75% Slope)
4. 50% Slope

In addition with each power supply characteristic, the following three shielding gas mixtures were utilized:

1. 25% Argon - 75% Helium
2. 50% Argon - 50% Helium
3. 100% Argon

Mixtures of these gases were used to evaluate advantages of the combination of both gases, such as the cleaning effect of the argon shielding and the increased penetration with helium.

Preliminary "T" stiffened panels were welded with only a single fillet. Each of these welds was examined by macrosectioning and bend testing. Results of this evaluation are described in paragraph 2.1.1.6.

Double fillet welded panels were also fabricated. These were measured for both out-of-plane distortion and shrinkage measurements. All fillet welds were made one weld at a time.

2.1.1.4 Starting and Control Characteristics - Initial fillet weld panels used a slow "run-in" electrode speed control in conjunction with a current relay for initiating the higher wire feed speed for welding. This feature is available in the Linde SCC-1 control and other manual and mechanized wire feed control units commercially available. It is a particularly desirable feature for obtaining smooth arc starting characteristics, minimizing poorly fused and excessively "built-up" weld beads at the starting point and during arc initiation, and reducing high current surges which cause arcing problems between the aluminum electrode and torch contact tube that ultimately contribute to electrode "burn-backs." Although the slow "run-in" feature is not necessary when using a constant voltage characteristic power supply, it is desirable for best aluminum weld performance. With drooping volt-ampere characteristic and constant current characteristic power supplies, the slow "run-in" feature is most desirable.

Weld settings are listed in paragraph 2.1.1.2.

2.1.1.5 Effect of Restraint on Weld Flatness - Initial "T" stiffened panels were welded in a fixture which provided minimal restraint. One weld pass was applied at a time. Using the best transverse and longitudinal distortion measurements from the screening samples, a predistortion fixture was designed to precamber the sheet material in both the transverse and longitudinal directions. This fixture incorporated a dual torch setup which allowed simultaneous fillet welds to be applied to each side of the "T" extrusions at the same time.

2.1.1.5.1 Dual Torch and Predistortion Fixture - All GMA welding was done automatically using the best conventional processes evaluated in the initial screening program. The dual torch setup was assembled by using a 7 ft. box beam and attaching a Linde OM-48 side beam track and carriage unit. The side beam was mounted in the flat position rather than the normal vertical position. Figures 2-5 and 2-6 illustrate the dual torch arrangement and the predistortion fixture assembly.

Back-up bars were machined from cold rolled steel. The dimensions were 48" L x 1" W x 1/2" T. Three bars were machined uniformly to permit a precamber in the longitudinal direction. These bars were uniformly tapered over 18" from each end to a .060" reduction in thickness, which was held constant for the center 12" length. The three bars were installed at the bottom of the beam, but the center bar was shimmed up .030" for its entire length. By forcing the extrusion down by screw adjustments from the top of the beam and with edge hold-downs, as shown in Figures 2-5 and 2-6, predistortion in both the transverse and longitudinal directions could be obtained.

2.1.1.5.2 Dual Torch Setup and Weld Equipment - The dual torch setup was mounted on a Linde OM-48 side beam carriage in conjunction with a Linde Type C electronic travel speed governor.

The dual torch arrangement was assembled, allowing the two fillet welds to be applied simultaneously. This helped equalize transverse weld metal shrinkage stresses to control vertical and longitudinal straightness of the extruded stiffener. Two 1,000-ampere continuously variable slope Tek-Tran D.C. power supplies (Figure 2-7) were used with 75% slope setting to provide a constant energy volt/ampere characteristic. Additional equipment employed was:

1. Two Airco AH-35C1 welding torches with modified nozzles for improved joint accessibility. (See Figures 2-5 and 2-6)
2. Two Airco AHF-C wire feeders. (Hung above the welding fixture)
3. Two Airco AHC-B controls with variable speed slow "run-in" wire feed for positive arc starting. (See Figure 2-7)
4. Linde OM-48 side beam and Linde type C electronic travel speed governor.

The torches were offset so that one torch was leading the other by 2-1/2".

<u>2.1.1.5.3 Power Supplies and Shielding Gas Characteristics</u> - All dual torch welding was performed utilizing two (2) Tek-Tran continuously variable slope, 1,000-ampere D.C. rectifier power supplies in conjunction with the welding equipment listed in paragraph 2.1.1.5.2. The final weld panels were fabricated using predistortion in both the transverse and longitudinal directions, and the preferred welding slope and gas mixtures as determined in the screening tests.

All panels were measured for out-of-plane distortion and shrinkage. The final twenty panels were then evaluated in further tests by Alcoa Engineering Design Division. Results are reported in paragraph 4.3.

<u>2.1.1.5.4 Starting and Control Characteristics</u> - Starting and controlling features for the dual torch setup were different for each of the welding torches.

The leading AH-35 torch was connected to an Airco AHC-B weld control panel. This panel included a MIG-Spot welding control feature with a slow "run-in" electrode feed mode. The MIG-Spot control allowed purging of the inert gas circuit to take place with the initial contact of the weld trigger. On the second contact of the trigger, the slow "run-in" mode initiated the wire feed and arc initiation took place upon contact of the electrode with the work.

The trailing AH-35 torch was also connected to an Airco AHC-B weld control panel. This panel was set for the normal manual welding circuitry with the "scratch-start" mode during the gas purging period. After both torches were purged, the trailing torch was switched to the slow "run-in" mode. This allowed positive and simultaneous arc initiation by both torches.

<u>2.1.1.5.5 Weld Parameters (Dual Torch)</u> - The welding parameters for the two welding torches were different, as the leading torch was preheating the base material. Twenty double fillet welded panels were fabricated using the following parameters:

Torch 1

200 amperes reverse polarity D.C.
19 arc volts
20° forward torch angle
37° torch angle from horizontal
3/64" 5556 electrode
80 ipm travel
30 cfh Ar + 30 cfh He shielding gas
9/16" I.D. torch nozzle

Torch 2 (Trailing 2-1/2")

190 amperes reverse polarity D.C.
18 arc volts
5° forward torch angle
45° torch angle from horizontal
80 ipm travel
30 cfh Helium + 30 cfh Argon shielding gas
9/16" I.D. torch nozzle
3/64" 5556 electrode

2.1.1.6 Results of Weld Screening Tests - The initial screening program was discussed previously but included varying the volt-ampere slope characteristic of the power supply and the shielding gas mixture.

The program was set up with the aid of a statistical analysis engineer who evaluated the data. The program consisted of parameters listed below (an additional slope of 50% was evaluated):

Gas Mixture	Power Supply: Constant Energy	Power Supply: Constant Voltage	Power Supply: Constant Current
100% Ar	1 Bend Spec. 1 Macro Spec.	1 Bend Spec. 1 Macro Spec.	1 Bend Spec. 1 Macro Spec.
75% He 25% Ar	"	"	"
50% He 50% Ar	"	"	"

Results of the bend specimens are listed in Table 2-2. All of the welds employing the constant energy (drooping volt-ampere) characteristic exhibited ductile bends. For this reason, the drooping volt-ampere characteristic was chosen for conventional GMA welding.

Two of the three shielding gas mixtures exhibited good weld soundness, good structure and penetration. They were the 25% Ar - 75% He and 50% Ar - 50% He mixtures. Because the 50% Ar - 50% He mixture gives greater versatility, i.e., sound welds over the widest ranges of arc voltage and welding current, this mixture was chosen. This evaluation was documented in "Inert Shielding Gases for Welding Aluminum," J. D. Dowd, Welding Journal, 1956.

Out-of-plane distortion and shrinkage measurements for the initial screening tests are listed in Table 2-3. All of the samples were quite uniform. Typical photomacrographs are shown in Figures 2-8 through 2-10 with remarks concerning the weld macrostructure for each gas mixture and power supply volt-ampere characteristic.

2.1.2 Pulsed GMA Welding - The pulsed power GMA welding evaluation continued with the same fabrication procedure as the conventional GMA process, that of applying 1/8" fillet welds with a minimal amount of distortion. Many parameters were evaluated in the conventional GMA process, and the results were used in the pulsed power GMA evaluation. The results from this evaluation included the following:

1. Shielding gas mixture 50% Ar - 50% He
2. Starting and controlling equipment
3. Torch angle (only one torch used)
4. 3/64" 5556 electrode diameter

The development parameters included evaluating the following power supplies:

1. Airco "Pulse Arc" (PA-2), 300 amp capacity, D.C. rectifier power supply (60 cycle pulsation) - (See Figure 2-11)
2. Dimetrics 1,000-ampere capacity D.C. rectifier power supply providing constant voltage or constant current characteristics with 2,000-24,000 H_z high frequency modulation (See Figure 2-12)

The same final specimen was used, that is, the 5456-H111 "T" extrusion and the 3/16" 5456-H116 sheet material as illustrated in Figure 2-1.

Since the purpose of initial welding program was to determine the best pulsating frequency characteristic, all distortion measurements, and macrostructure results are listed in this section. Initial procedure specimens were joined using only single fillet welds without predistortion. These were evaluated by taking macrosections from the end of the weldment and a bend-fracture test to determine the weld soundness, fillet size and penetration characteristics. When optimum parameters were developed to produce a 1/8" fillet size with proper penetration and soundness, double fillet welded panels were fabricated to measure shrinkage and out-of-plane distortion. A total of seventeen (17) "T" stiffened panels were fabricated using high frequency pulsation. The results of these final panels are listed in Section 4.0 (fabricated without predistortion).

2.1.2.1 Equipment and Fixture - The single fillet weld panels were fabricated in the same fixture as the conventional GMA welds (Figure 2-3). As mentioned before, this fixture positioned the "T" extrusion in the center of the sheet and held it securely so that twisting would not occur; however, the 3/16" sheet was allowed to move.

The welding equipment used in this phase of the progr is listed below:

1. Linde SEH-2 wire feed head
2. Linde HW-13 torch
3. Linde SCC-1 control with slow "run-in" wire feed starting feature
4. Linde OM-48 side beam carriage assembly with Linde type "E" electronic governor.

The Airco "Pulse Arc" and the Dimetrics high frequency modulated D.C. power supplies were used in the initial evaluation.

<u>2.1.2.2 Basic Parameters</u> - The initial welding program entailed evaluating various pulsating characteristics of D.C. power supplies. A 300-ampere capacity Airco type PA-2 "Pulse Arc" power supply was used to provide low frequency cycling between a peak amperage and a lower "back-ground" current. A 1,000-ampere capacity Dimetrics power supply was employed to provide high frequency modulated D.C. as well as a low frequency cycling between high and low current levels. The following pulsing characteristics were evaluated:

1. Airco PA-2 - 60 cycles per second
2. Dimetrics - high frequency modulated D.C.

a. 25,000 pulses/second
b. 20,000 pulses/second
c. 15,000 pulses/second
d. 10,000 pulses/second
e. 5,000 pulses/second
f. 20,000 pps with 600 cps

The initial fillet welds were fabricated by automatic GMA welding a vertical 1/8" thick 5456 sheet to a horizontal 3/16" 5456 sheet with 3/64" diameter 5556 alloy electrode. A 1/8" fillet weld was applied to only one side of the joint. A macrosection was prepared to ascertain the proper depth of penetration and fillet weld size, as weld parameters were varied. A bend test was conducted to fracture the fillet weld in order to exami the uniformity of penetration and weld soundness. Sections of welds illustrating each test condition were metallographically examined to further evaluate the weld soundness, structure and geometry.

Following these evaluations, double fillet welded specimens were made in the fixture described in Paragraph 2.1.1.5.1 and Figures 2-5 and 2-6 with 48" long 5456-H111 "T" extrusions centered on the 4" width of 3/16" 5456-H116 sheet. Since only one power supply of each type was available, the dual weld technique could not be applied. The material was premarked by the Engineering Properties and Design Division to permit accurate determination of shrinkage and distortion resulting from welding. Results of measurements are listed in Table 2-4. Listed in Table 2-5 are the weld parameters used and the results of the bend tests.

All of these welds were made with a gas mixture of 50% Ar + 50% He and at a speed of 80 in./min., except for those made with the Airco PA-2 power supply. At speeds of 80 ipm, skips resulted in the weld when using the low frequency pulsing Airco PA-2 power supply. Consequently, a slower speed of 40 ipm was employed, resulting in a slightly larger but uniform fillet weld with the PA-2 power source, as shown in Figure 2-13.

2.1.2.3 Welding Parameters - From the data obtained in the initial weld evaluation, the optimum D.C. pulsation was determined to be 20,000 pps D.C. modulation with a 600 cps pulsation between high and low current settings. Macrostructure of the high frequency weld is shown in Figure 2-14. Seventeen double fillet welded panels were fabricated with this method and the following weld parameters:

3/64" diameter 5556 electrode
210 amperes average current
20 arc volts
30 cfh Helium + 30 cfh Argon shielding gas
Linde HW-13 torch with 1/2" I.D. nozzle
Torch angles - 20° forward, 51° from horizontal
80 in./min. travel speed

Since only one Dimetrics power supply was available, the fillet welds were applied one at a time. Fixturing was sufficient to maintain intimate contact between the parts, but no (longitudinal or transverse) predistortion to control flatness was employed.

TABLE 2-1

HEAT INPUT PER WELD PROCESS

Electron Beam Weldtrusion - 2,508 joules/in.

High Frequency GMAW - 6,300 joules/in.

Conventional GMAW - 5,415 joules/in.

Conventional GMAW Butt Weld - 11,392 joules/in. (2-sided weld)

Conventional GMAW Butt Weld - 11,142 joules/in. (1 side only)

Plasma-GMAW Butt Weld - 13,698-21,774 joules/in.

Sciaky E.B. Butt Weld - 3,000 joules/in.

High Frequency Resistance Weld - 65,000 joules/in.

Explosion Welding (Estimated) 88-112 joules/in.

TABLE 2-2

FILLET WELD BEND TEST RESULTS

Original Weld Specimen Number	Weld Parameters			Distortion Specimen Number (Table 2-3)	Mode of Weld (Power Supply)	Gas Mixture (%)	Bend Test (1)
A-10-2-6	215 A	20 V	80 ipm	5	75% Slope (C.E.)	50 Ar - 50 He	Ductile bend
A-10-3-1	210 A	21 V	80 ipm	11	75% Slope (C.E.)	25 Ar - 75 He	Ductile bend
A-10-8-1	210 A	19 V	80 ipm	4	75% Slope (C.E.)	100 Ar	Ductile bend
B-10-9-2	210 A	19 V	80 ipm	3	99.9% Slope (C.C.)	100 Ar	Fractured
B-10-9-3	210 A	21 V	80 ipm	12	99.9% Slope (C.C.)	25 Ar - 75 He	Fractured
B-10-10-1	210 A	20 V	80 ipm	6	99.9% Slope (C.C.)	50 Ar - 50 He	Fractured
C-10-10-2	210 A	20 V	80 ipm	8	0.0% Slope (C.V.)	50 Ar - 50 He	Fractured
C-10-10-3	210 A	20 V	80 ipm	9	0.0% Slope (C.V.)	25 Ar - 75 He	Ductile bend
C-10-11-1	205 A	19 V	80 ipm	2	0.0% Slope (C.V.)	100 Ar	Fractured
C-10-11-2	210 A	19 V	80 ipm	1	50% Slope (C.E.)	100 Ar	Fractured
Specimen A	210 A	19 V	80 ipm	7	50% Slope (C.E.)	50 Ar - 50 He	--
Specimen B	210 A	19.5 V	80 ipm	10	50% Slope (C.E.)	25 Ar - 75 He	--

(1) No fracture occurred in the ductile bends

TABLE 2-3

SUMMARY OF DISTORTION MEASUREMENTS

Spec No.	Change in Length of Sheet, in. Longitudinal 0.01" Scale	Change in Length of Sheet, in. Longitudinal .001" Dial	Change in Length of Sheet, in. Transverse Micrometer	Sheet Warpage, in. .001" Dial	Change in Length of Extrusions, in. Longitudinal 0.01" Scale	Change in Length of Extrusions, in. Longitudinal .001" Dial
1	-.05	-.037	-.010	.039	0	.009
2	-.06	-.049	-.003	.048	0	-.001
3	-.04	-.040	-.018	.045	0	.003
4	-.06	-.045	-.016	.046	0	.004
5	-.04	-.043	-.004	.047	0	.003
6	-.04	-.039	-.004	.045	0	.004
7	-.05	-.034	-.007	.047	.01	.010
8	-.04	-.036	-.007	.044	.01	.011
9	-.04	-.037	-.010	.040	.02	.012
10	-.04	-.036	-.006	.042	.01	.011
11	-.04	-.042	-.010	.045	0	.006
12	-.05	-.046	-.009	.038	.01	.013

Note: (1) Scale measurements are along the contour of the part. Dial and micrometer measurements are straight-line distances between gage points.
(2) Spec numbers are the same as listed in Table 2-2 under "Distortion Specimen Number."

TABLE 2-4

SUMMARY OF DISTORTION MEASUREMENTS

	Change in Length of Sheet, in.			Sheet Warpage, in.	Change in Length of Extrusions, in.	
	Longitudinal				Longitudinal	
Spec No.	0.01" Scale	.001" Dial	Transverse Micrometer	.001" Dial	0.01" Scale	.001" Dial
28 (E-10-30-7) (25,000 pps)	--	-.051	0	+.048	--	-.002
29 (E-10-30-6) (20,000 pps)	--	-.048	+.001	+.046	--	-.003
30 (E-10-30-5) (15,000 pps)	--	-.045	+.002	+.048	--	0
14 (D-10-18-4) (60 cps Airco)	-.04	-.039	-.013	+.045	0	+.007
15 (E-10-30-2) (20,000 pps + 600 cps)	-.04	-.036	-.014	+.047	0	+.003
17 (E-10-30-3) (5,000 pps)	-.08*	-.037	-.013	+.049	+.03*	+.008
18 (E-10-30-1) (10,000 pps)	-.05	-.043	-.011	+.048	0	+.009

*These readings may be in error.

Note: Scale measurements are along the contour of the part. Dial and micrometer measurements are straight-line distances between gage points.

TABLE 2-5

FILLET WELD BEND TEST RESULTS

Original Weld Specimen Number	Weld Parameters	Pulsating Frequency	Gas Mixture	Bend Test
E-10-29-1	210 A 20 V 80 ipm	25,000 pps	30 cfh Ar/30 cfh He	Fractured
E-10-29-2	210 A 20 V 80 ipm	20,000 pps	30 cfh Ar/30 cfh He	Fractured
E-10-29-3	210 A 20 V 80 ipm	15,000 pps	30 cfh Ar/30 cfh He	Fractured
E-10-29-4	210 A 20 V 80 ipm	10,000 pps	30 cfh Ar/30 cfh He	Fractured
E-10-29-5	210 A 20 V 80 ipm	5,000 pps	30 cfh Ar/30 cfh He	Fractured
E-10-30-1	210 A 20 V 80 ipm	20,000 pps 600 cps	30 cfh Ar/30 cfh He	Fractured

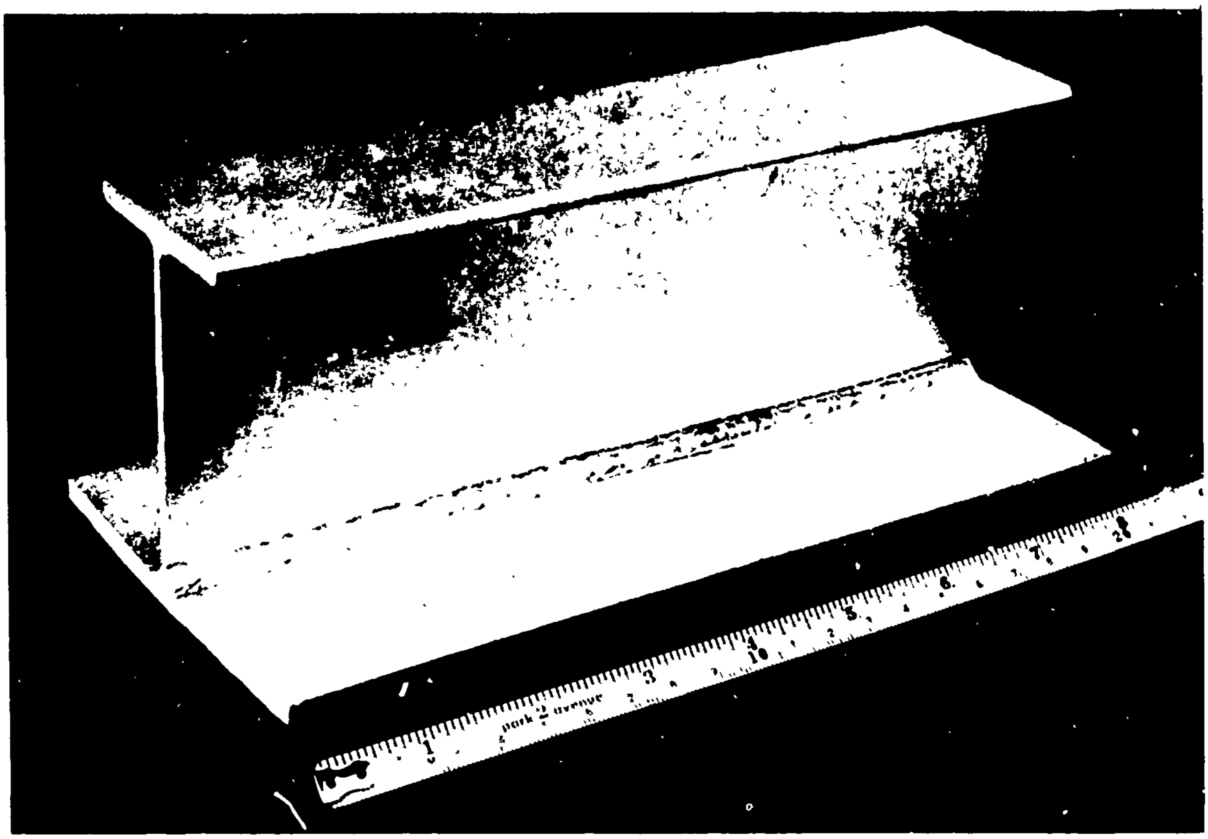


FIG. 2-1- FILLET WELD SHOWING 5456-H111 "T" EXTRUSION AND 3/16" 5456-H116 SHEET MATERIAL

FIG. 2-2- BUTT WELDED 3/16" 5456-H116 SHEET

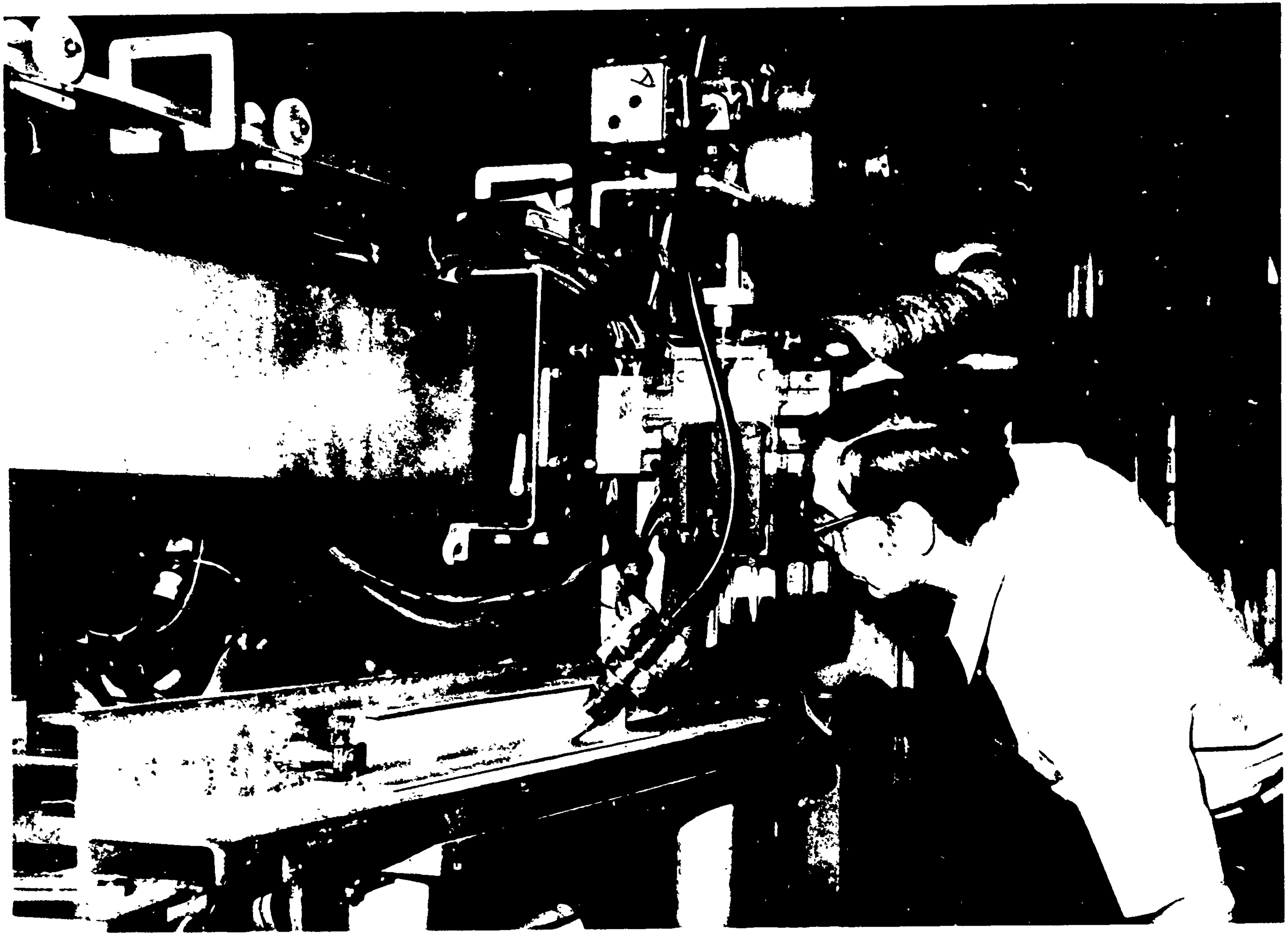


FIG. 2-3- WELDING EQUIPMENT USED TO FABRICATE INITIAL "T" STIFFENED PANELS

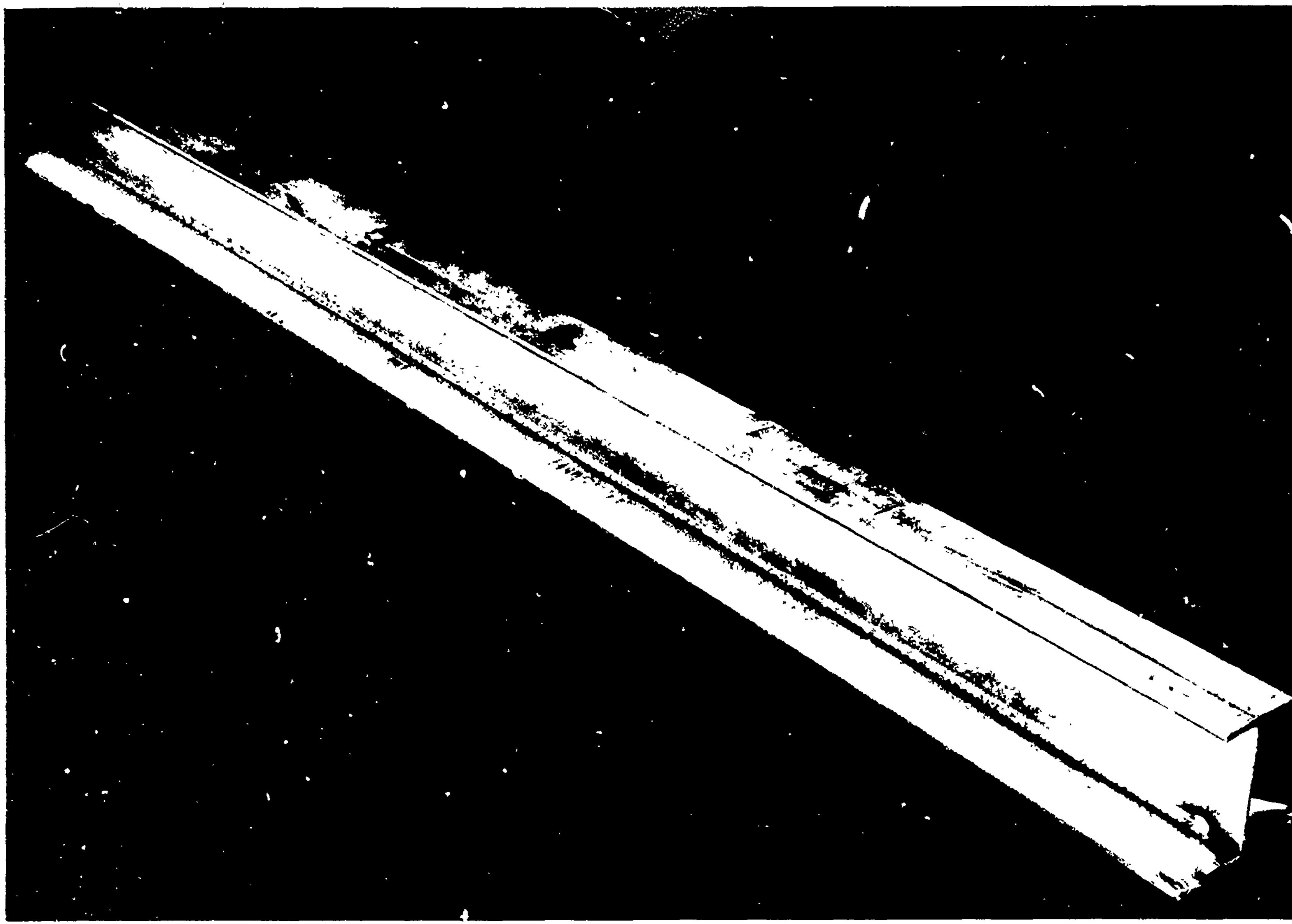


FIG. 2-4 - TYPICAL 48" LONG "T" STIFFENED TEST PANEL WITH 1/8" FILLET SIZE

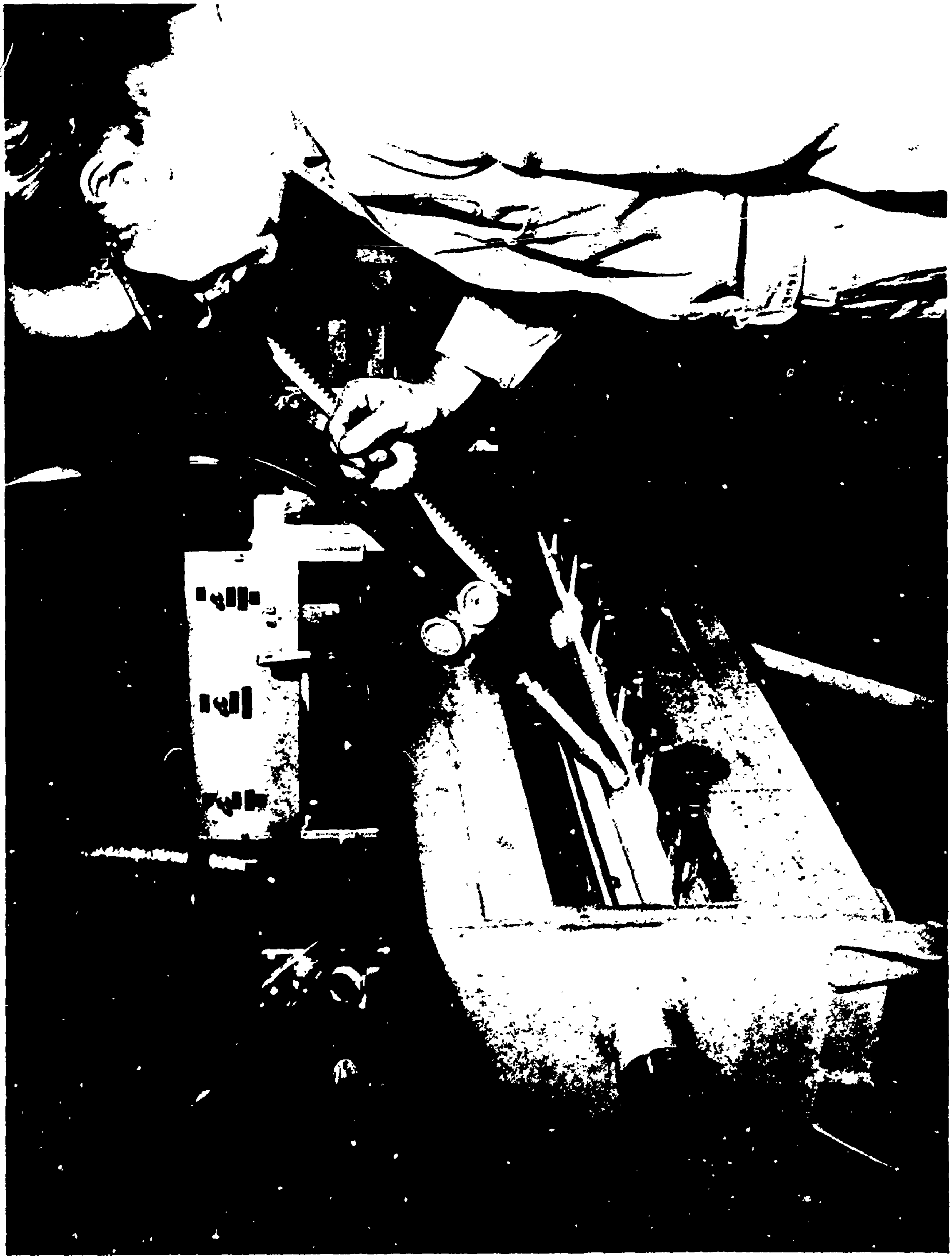


FIG. 2-5- CLOSE-UP OF AIRCO AH-35 TORCH WITH MODIFIED EXTENDED NOZZLE AND THE PRE-DISTORTION EQUIPMENT UTILIZED

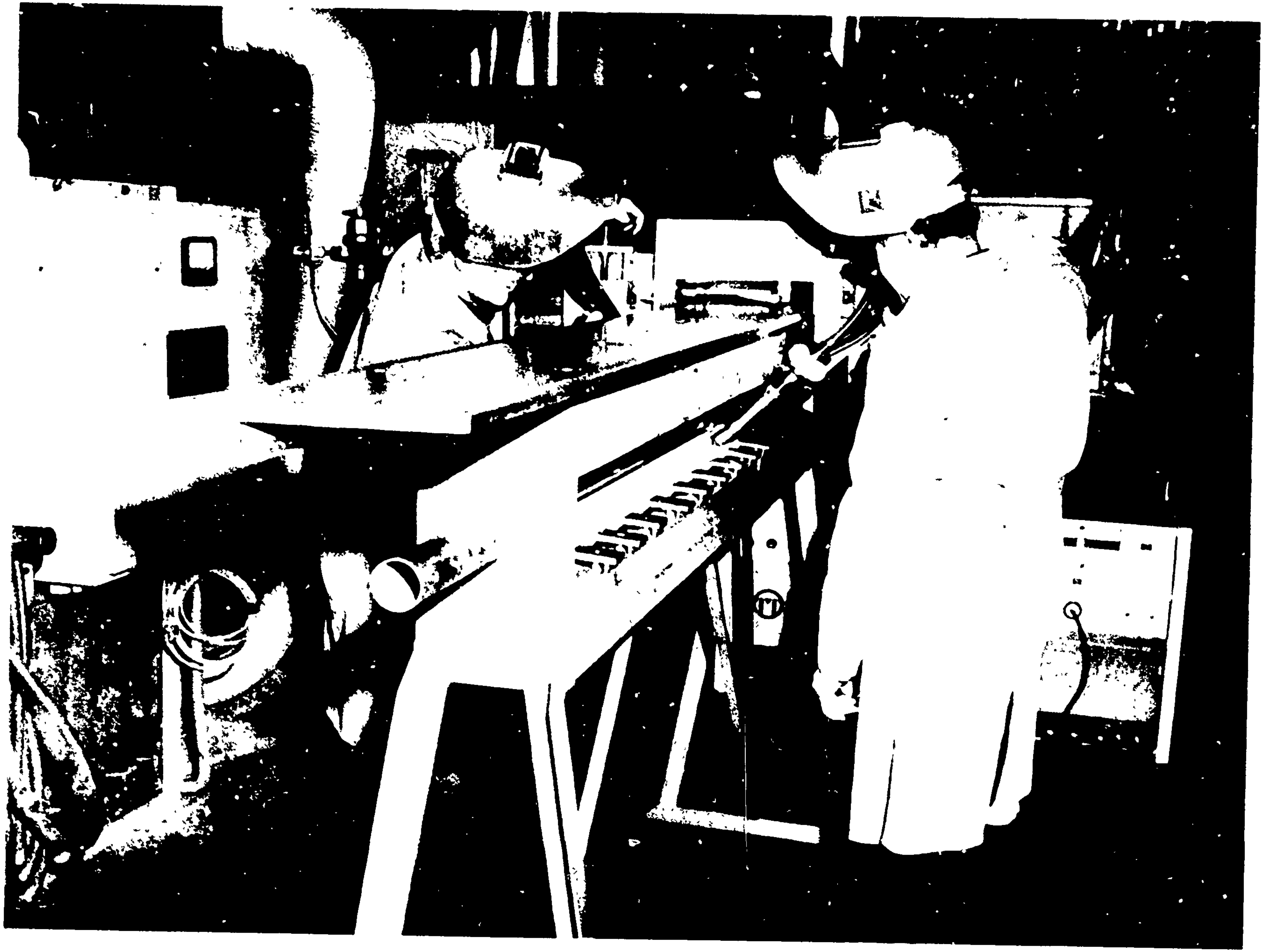


FIG. 2-6- DUAL TORCH SETUP SHOWING LINDE SIDE BEAM IN THE FLAT POSITION

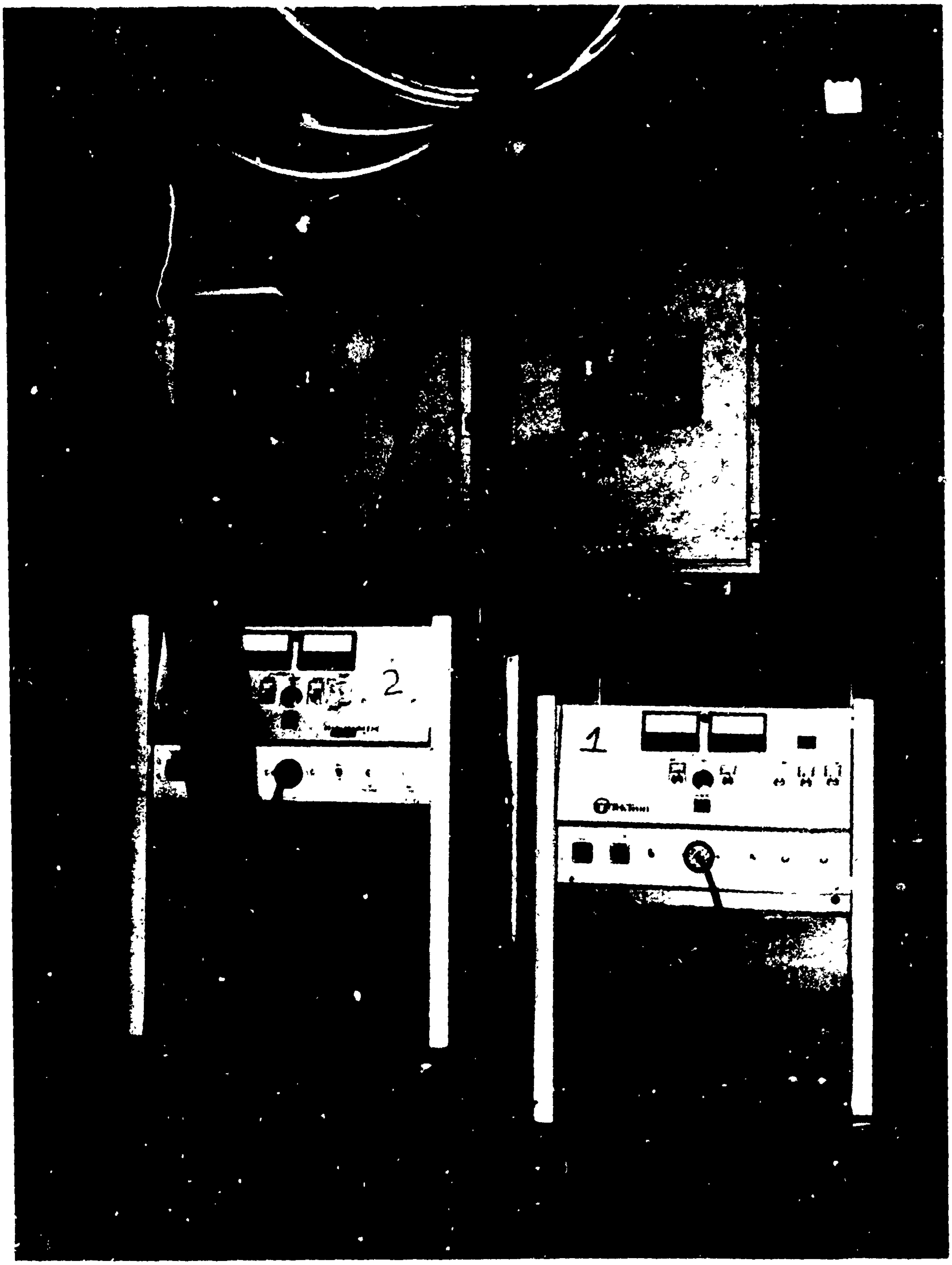


FIG. 2-7- TEK-TRAN POWER SUPPLIES AND AIRCO AHC-B CONTROLS UTILIZED ON DUAL TORCH SETUP

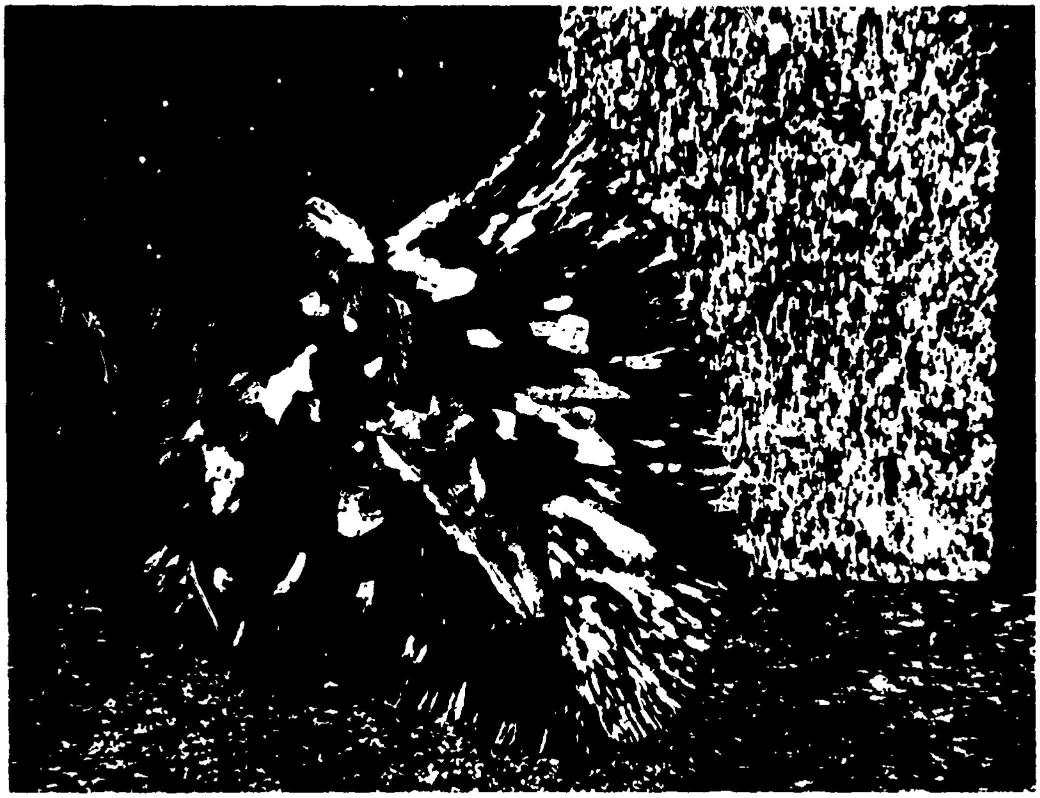


FIG. 2-8

CONSTANT ENERGY POWER SUPPLY

MAG. 18X ETCH: ELECTROPOLISH, POLARIZED LIGHT

SPECIMEN NO. 244348-1 (PICTURED ABOVE)

GAS MIXTURE - 50% Ar + 50% He

COMMENTS:
a. Small amount of porosity.
b. Large columnar grain.
c. Good root fusion.

SPECIMEN NO. 244348-2

GAS MIXTURE - 25% Ar + 75% He

COMMENTS:
a. Small amount of porosity.
b. Few columnar grains.
c. Good root fusion.

SPECIMEN NO. 244348-3

GAS MIXTURE - 100% Ar

COMMENTS:
a. Significant amount of porosity.
b. Few columnar grains.
c. Unfused zone extending into the root of weld .013".

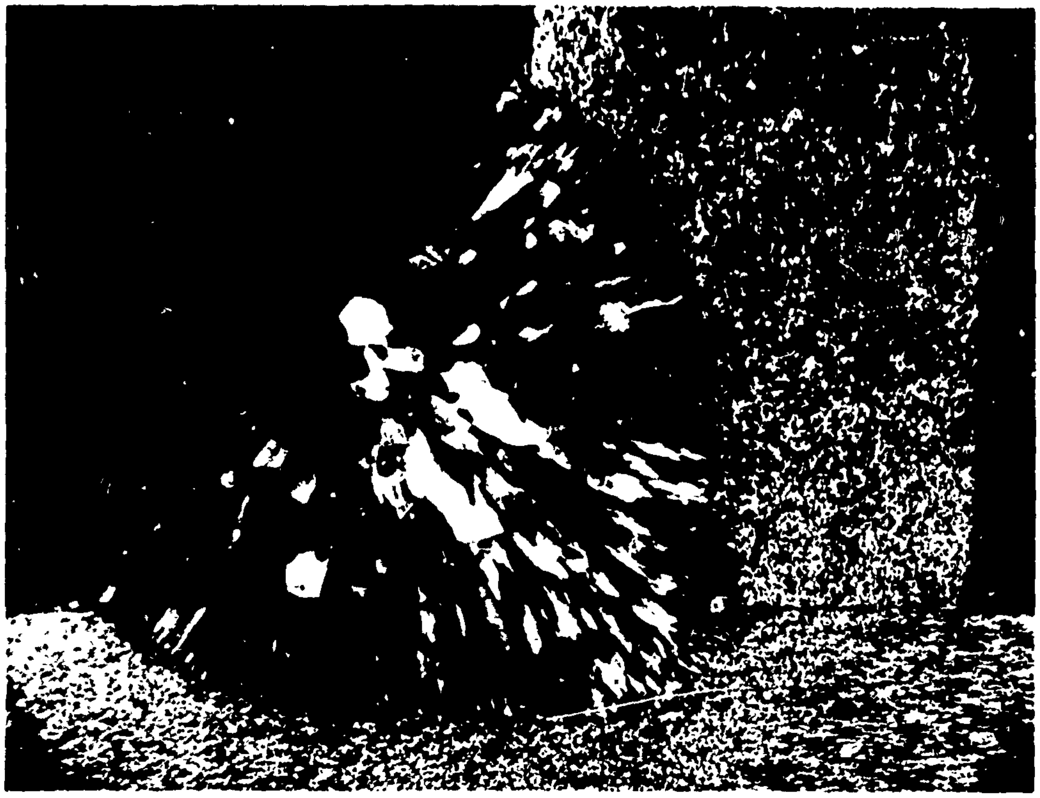


FIG. 2-9

CONSTANT CURRENT POWER SUPPLY

MAG. 18X ETCH: ELECTROPOLISH, POLARIZED LIGHT

SPECIMEN NO. 244348-6 (PICTURED ABOVE)

GAS MIXTURE - 50% Ar + 50% He

COMMENTS:
a. Weld metal appeared very good.
b. Grain structure good.
c. One gas cavity in the root fusion area.

SPECIMEN NO. 244348-5

GAS MIXTURE - 25% Ar + 75% He

COMMENTS:
a. Weld metal appeared very sound.
b. Grain structure good.
c. Good root fusion.

SPECIMEN NO. 244348-4

GAS MIXTURE - 100% Ar

COMMENTS:
a. Several large internal gas voids.
b. Elongated grains, but smaller than the columnar grains.
c. Good root fusion.

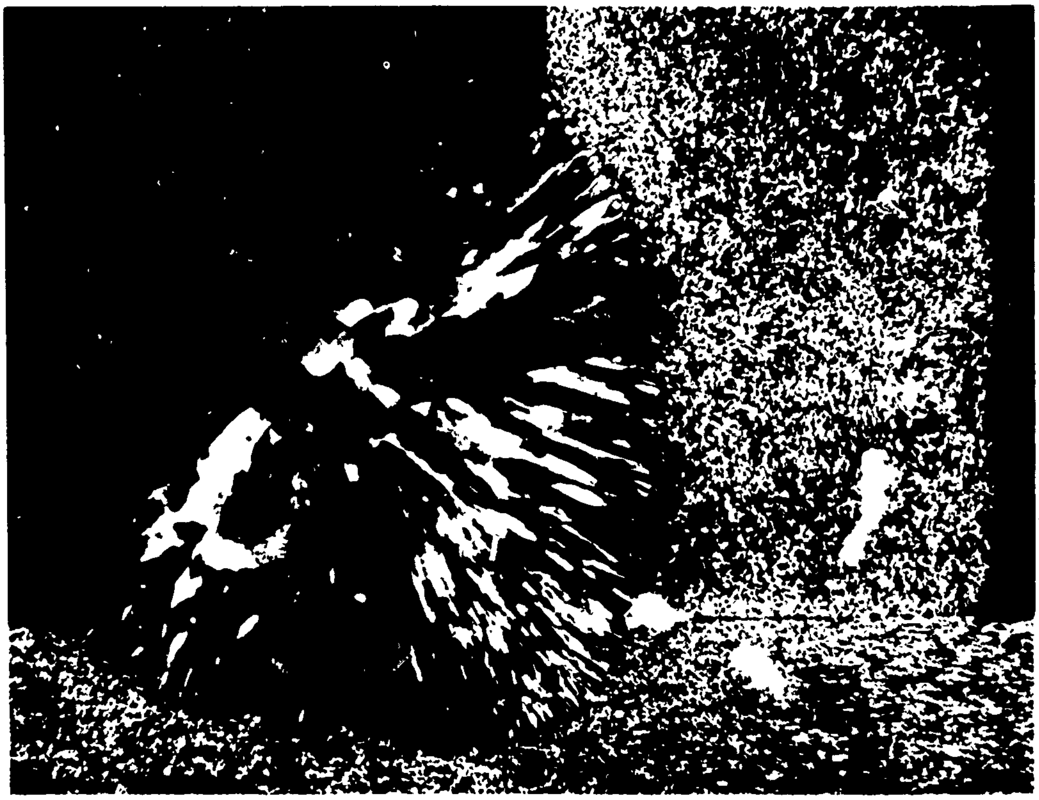


FIG. 2-10

CONSTANT VOLTAGE POWER SUPPLY

MAG. 18X ETCH: ELECTROPOLISH, POLARIZED LIGHT

SPECIMEN NO. 244348-7 (PICTURED ABOVE)

GAS MIXTURE - 50% Ar + 50% He

COMMENTS:
a. Minimal amount of voids in the weld bead.
b. Large elongated grains.
c. Large gas cavity in the root fusion area.

SPECIMEN NO. 244348-8

GAS MIXTURE - 25% Ar + 75% He

COMMENTS:
a. Weld metal appeared very good.
b. Grain structure good.
c. Good root fusion.

SPECIMEN NO. 244348-9

GAS MIXTURE - 100% Ar

COMMENTS:
a. Weld metal appeared very good.
b. Grain structure good.
c. Good root fusion.

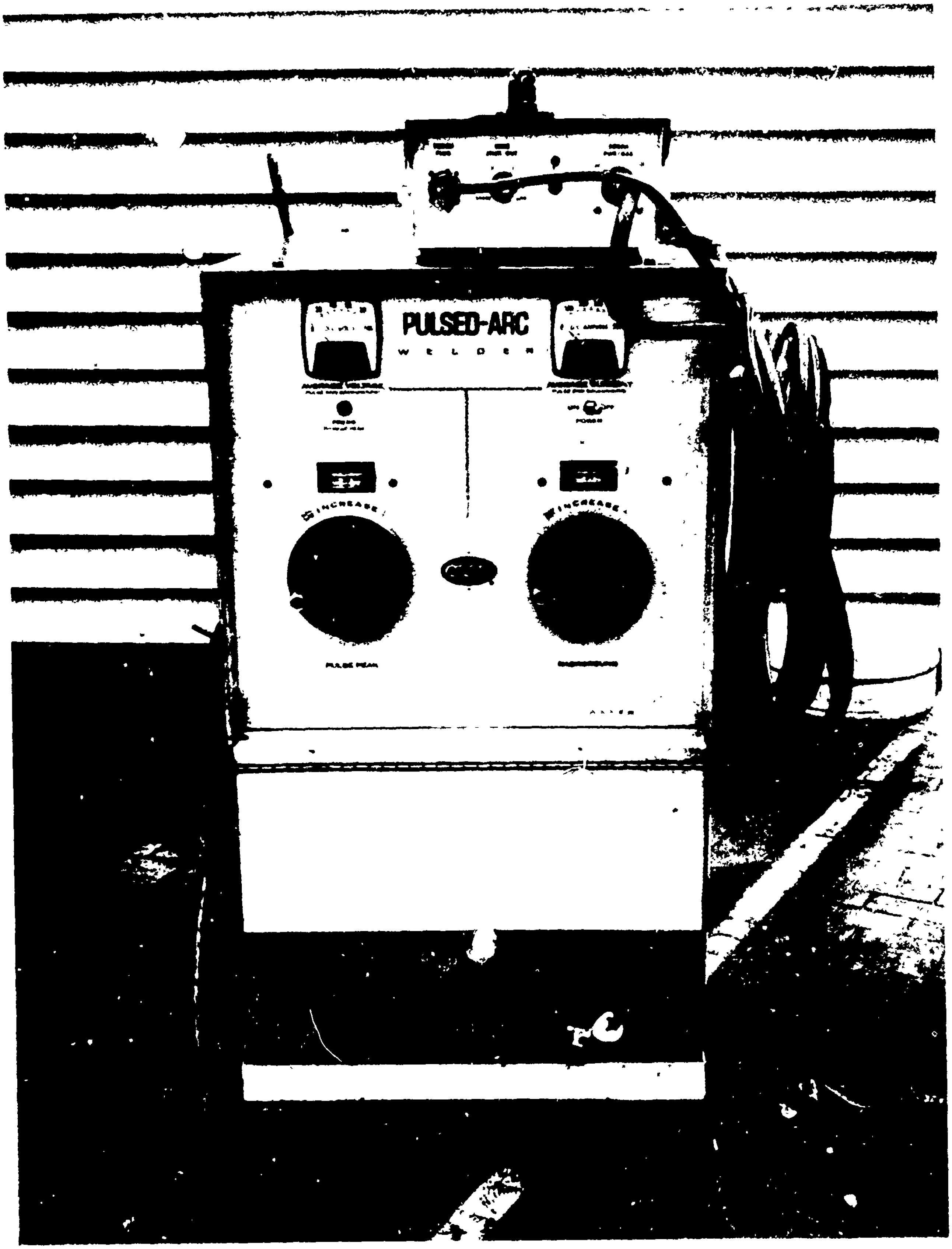


FIG. 2-11 - AIRCO /PA-2 "PULSED ARC" POWER SUPPLY USED ON LOW FREQUENCY PULSED GMAW FILLET WELDING

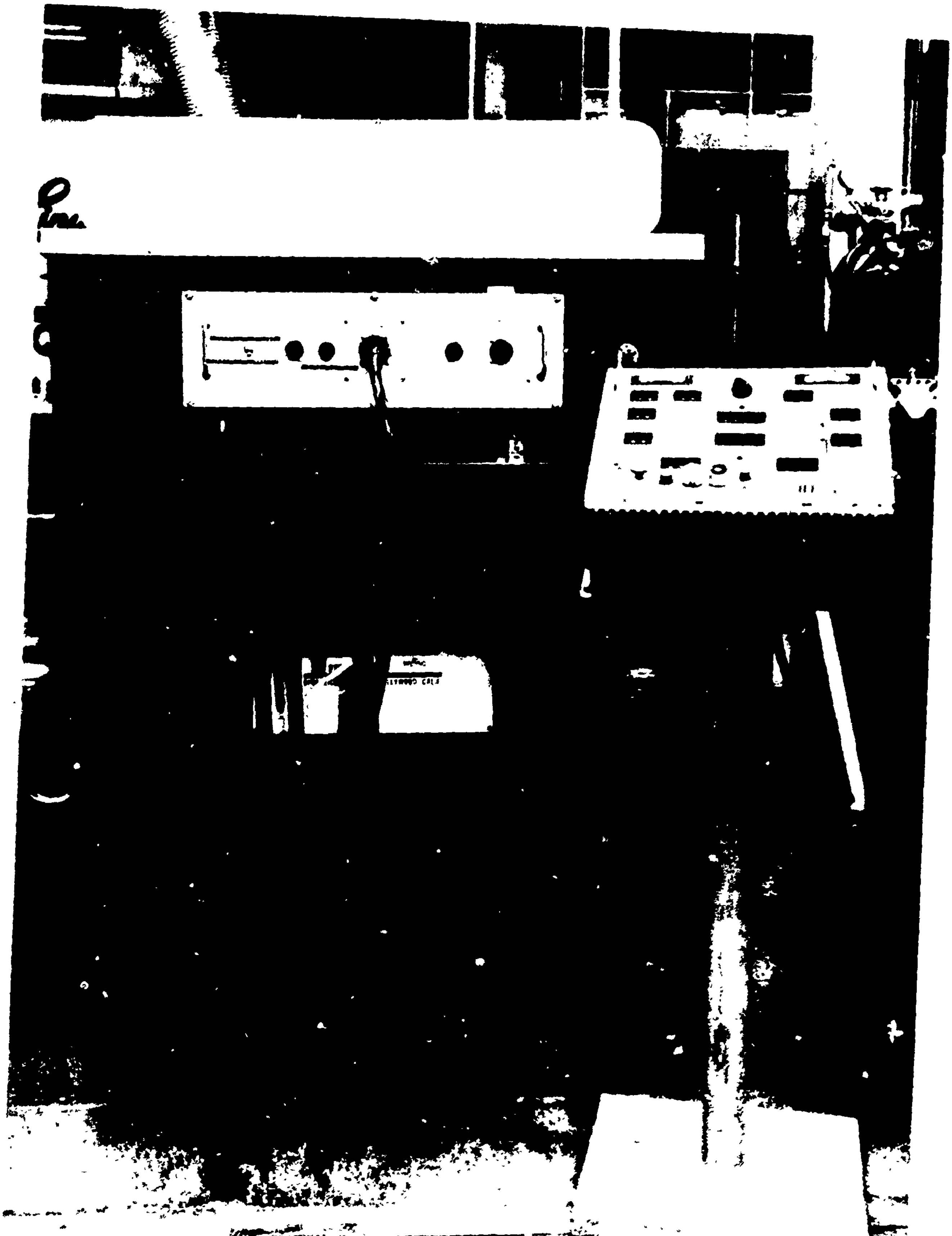


FIG. 2-12- DIMETRICS 1000 AMP. D.C. RECTIFIER POWER SUPPLY WITH ADDED HI-FREQUENCY MODULATION OF D.C.

FIG. 2-13

AIRCO PA-2 POWER SUPPLY

GAS MIXTURE - 50% Ar + 50% He

MAG. 18X ETCH: ELECTROPOLISH, POLARIZED LIGHT

SPECIMEN NO. 244367-1

FREQUENCY - 60 CPS

COMMENTS:
a. Significant amount of porosity.
b. Grain structure good.
c. Large gas cavity in root area.

FIG. 2-14

DIMETRICS PULSE POWER SUPPLY

GAS MIXTURE - 50% Ar + 50% He

MAG. 18X ETCH: ELECTROPOLISH, POLARIZED LIGHT

SPECIMEN NO. 244367-7 (PICTURED ABOVE)

FREQUENCY - 20,000 PPS + 600 CPS

COMMENTS:
a. Weld metal appeared very sound.
b. Good grain structure.
c. Good root fusion.

SPECIMEN NO. 244367-6

FREQUENCY - 5,000 PPS

COMMENTS:
a. Weld metal appeared very good.
b. Grain structure good.
c. Good root fusion.

SPECIMEN NO. 244367-5

FREQUENCY - 10,000 PPS

COMMENTS:
a. Small amount of porosity.
b. Grain structure good.
c. Large gas cavity in weld root.
d. Segregated constituent at weld passes.

SPECIMEN NO. 244367-4

FREQUENCY - 15,000 PPS

COMMENTS:
a. No significant porosity in weld bead.
b. Grain structure good.
c. Good root fusion.
d. Segregated constituent at weld passes.

SPECIMEN NO. 244367-3

FREQUENCY - 20,000 PPS

COMMENTS:
a. Small amount of porosity.
b. Grain structure good.
c. Good root fusion.
d. Segregated constituent at weld passes.

SPECIMEN NO. 244367-2

FREQUENCY - 25,000 PPS

COMMENTS:
a. Small amount of porosity.
b. Grain structure good.
c. Good root fusion.

2.1.3 High-Frequency Resistance Welding - High-frequency resistance welding of "T" extrusions to sheet was carried out by Battelle Columbus Laboratories. The beam geometry for welding trials consisted of a 20' long length of 5456-H111 3" high "T" extrusion welded to a 4" weld strip of 3/16" thick 5456-H116 sheet. (See Figure 1-1). All welding parameters, fixturing and final weld joints were completed by Battelle Columbus Laboratories.

2.1.3.1 Welding Equipment Fixturing - Battelle's high-frequency resistance-welding facility consists of a Thermatool Model VR280 high-frequency resistance-welding power supply, a hydraulic roll-drive system that pull the materials through the welding station, material guiding tools, instrumentation and other equipment needed to carry out experimental welding. This equipment was originally used to experimentally produce titanium alloys structurals.

As the aluminum component parts enter the welding station, they are brought together in a "Vee" configuration. This is shown schematically in Figure 2-15. The extrusion was fed straight into the welding station while the sheet element was fed through an arc so as to produce a 7° angle at the point where contact is made between the sheet and web of the "T". Welding of the sheet to the "T" takes place at this point. The 7° angle has been determined to be optimum for aluminum in prior welding applications and was held constant throughout the program. (See Figure 2-16). The high-frequency current enters the material being welded from sliding contacts and travels along the opposite surfaces of the "Vee" formed by the moving work piece. The edges of the work piece which form the "Vee" are heated to the temperature required for welding. At the point of the "Vee" apex, mechanical pressure forces the two work pieces together to complete the weld. The high-frequency alternating current has the characteristic of traveling on the opposite surfaces of the "Vee." This effect will be greater when the two surfaces of a conductor carrying a current are placed close to each other with a small air gap between them. This "proximity effect" results in the current concentrating in the opposing surfaces of the conductors and this heats the surface by electrical resistance to a high temperature, in a very short time. Thus in the high-frequency resistance-welding process, large current densities and higher rates of resistance heating are achieved in narrow zones on the opposing surfaces of the "Vee."

The tooling used in high-frequency resistance welding forms the sheet into the "Vee" configuration and controls this configuration during welding. Another important purpose of the tooling is to force the parts together at the proper time and temperature and hold the parts together until the weld is accomplished. The roll-drive equipment is capable of accelerating the parts to be welded from speeds of 30 to 300' per minute within 3 to 4' of the start. In order to engage the pull-out roll-drive equipment, aluminum leader sections were welded on the lead end of extrusion and sheet elements. (See Figure 2-17).

2.1.3.2 Development of Basic Welding Parameters - Normally, the contact electrodes for the extrusion and sheet would be placed in close proximity, upstream of the squeeze rolls. The first trials indicated that there was a great difference in the mass of the two parts; i.e., the 3/16" flat sheet and the 1/8" thick stem of the "T".

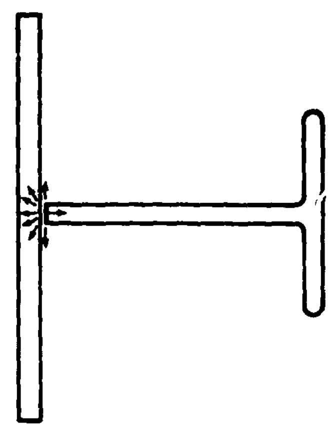


FIG. 2-18- CROSS SECTION OF "T" STIFFENED PANEL EXTRUSION AND SHEET ELEMENTS IN POSITION TO BE WELDED.

Arrows indicate flow of heat away from the welded joint.

This condition would make it difficult to obtain a set of welding conditions that would provide the right amount of heating on each side of the welding "Vee" to produce a good weld between the parts. The fact that aluminum is a good electrical and thermal conductor with a melting point around 1200°F also contributes to making the welding conditions relatively critical. Numerous trials were made in an unsuccessful attempt to obtain a full fusion weld between the sheet and extrusion. These trials included the following:

1. Variation and upset force on the squeeze rolls between 600 and 900 psi, across the joint.
2. Variation in the upset distance between 0.060" and 0.100".
3. Variation of the input electrical weld power.
4. Variation of the travel speed between 150 and 175 feet per minute.
5. Movement of the electrode contacting the sheet element from 1-1/2 to 8" upstream from the squeeze rolls.
6. Movement of the electrode contacting the extrusion element from 1-1/2 to 3" upstream from the squeeze roll and from a near end of the web of the "T" to a location close to the flange of the "T".

Trials with the best combinations of the above variables generally resulted in "welds" similar to that shown in Figure 2-19. During welding there was a gathering of excessive molten metal in the "Vee," ahead of the squeeze point followed by an explosive expulsion of the metal which resulted in a stitching between the parts. Such "welds" had a little ductility or strength. Using higher currents with higher speeds and a 1/8" diameter, 150 cu. ft. per minute jet of argon gas to blow away excessive molten metal resulted in making some rather strong welds. These welds, however, had low ductility and still possessed a stitched geometry with skips in between, making them unacceptable. (See Figure 2-20).

2.1.3.3 Addition of In-Line Heating Equipment and Further Weld Parameter Development - The initial failures described above precluded the construction of an in-line heating unit so as to significantly increase the heat input to the sheet element. The theory of operation of the in-line heater is depicted in Figure 2-21. This in-line heater would provide another "heating Vee" (proximity heating) which would concentrate heat on the side of the flat sheet only. Several units were constructed to arrive at the unit shown in Figure 2-22 which was used to make the beams for the weld evaluation. The design and fitting of such a device is complicated by the need to have it parallel the sheet at a distance of 0.050" or less without touching the sheet at any point. Touching the sheet would result in arcing and short circuiting the electrical current. In addition, it is necessary that in-line heater be water cooled to prevent melting of the conductor carrying the welding current which is on one side of the heater. Using in-line heater, the sheet to extrusion weld was made without stitching. (See Figure 2-23). These welds, however, were pulled apart rather easily and appeared to be brittle. Increasing the welding current resulted in a return of the stitching phenomena. (See Figure 2-24). After some additional trial, it was decided to use flame preheating of the sheet to 450^{O}F in addition to the in-line heater. The welds produced under this procedure could not be pulled apart and could be bent over without fracturing as shown in Figure 2-25. Typical cross sections of welds produced are shown in Figure 2-26.

2.1.3.4 Welding of 4' Long Beams for Evaluation - While the procedure outlined in Paragraph 2.1.3.3 accomplished the proper welding of the sheet to extrusion elements, it also resulted in the welded beams gradually bowing as they cooled on the run-out table. (See Figure 2-27). Additional experimentation was not possible within the time and cost scope and it was therefore agreed that the evaluation of the high-frequency resistance welding of "T" stiffened panels should be made on beams having the optimum weld even though they would possess considerable bow due to the need to flame preheat the sheet element. It is believed that additional development of the in-line heating equipment would eliminate the need to preheat the sheet. Beams welded without the use of preheat were remarkably flat and free of distortion in both the longitudinal and transverse directions.

The beams for weld evaluation were made using the following process parameters:

1. Travel speed - 150' per minute
2. Electrical power input - 12.5KV (dial 460)
3. Electrical current - 13.0 amperes
4. Upset distance - 0.60"
5. Upset force (total pressure) - 4,000 lbs.
6. Vee angle - 7°
7. Preheated sheet to 400°F
8. Argon jet flow - 150 cu. ft. per minute
9. Extrusion contact to squeeze point distance - 3"
10. Sheet contact to squeeze point distance - 8"

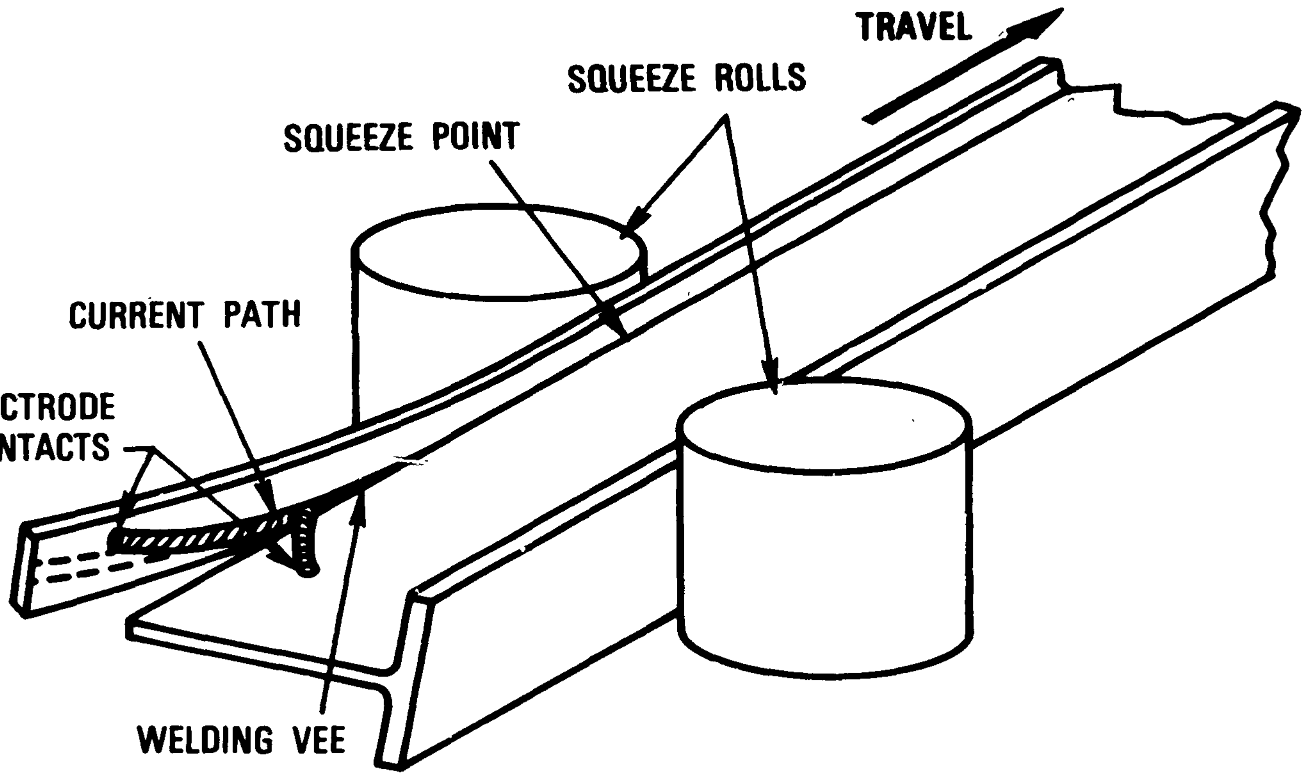


FIG. 2-15- SCHEMATIC OF "T" STIFFENED PANEL BEING WELDED BY HFRW

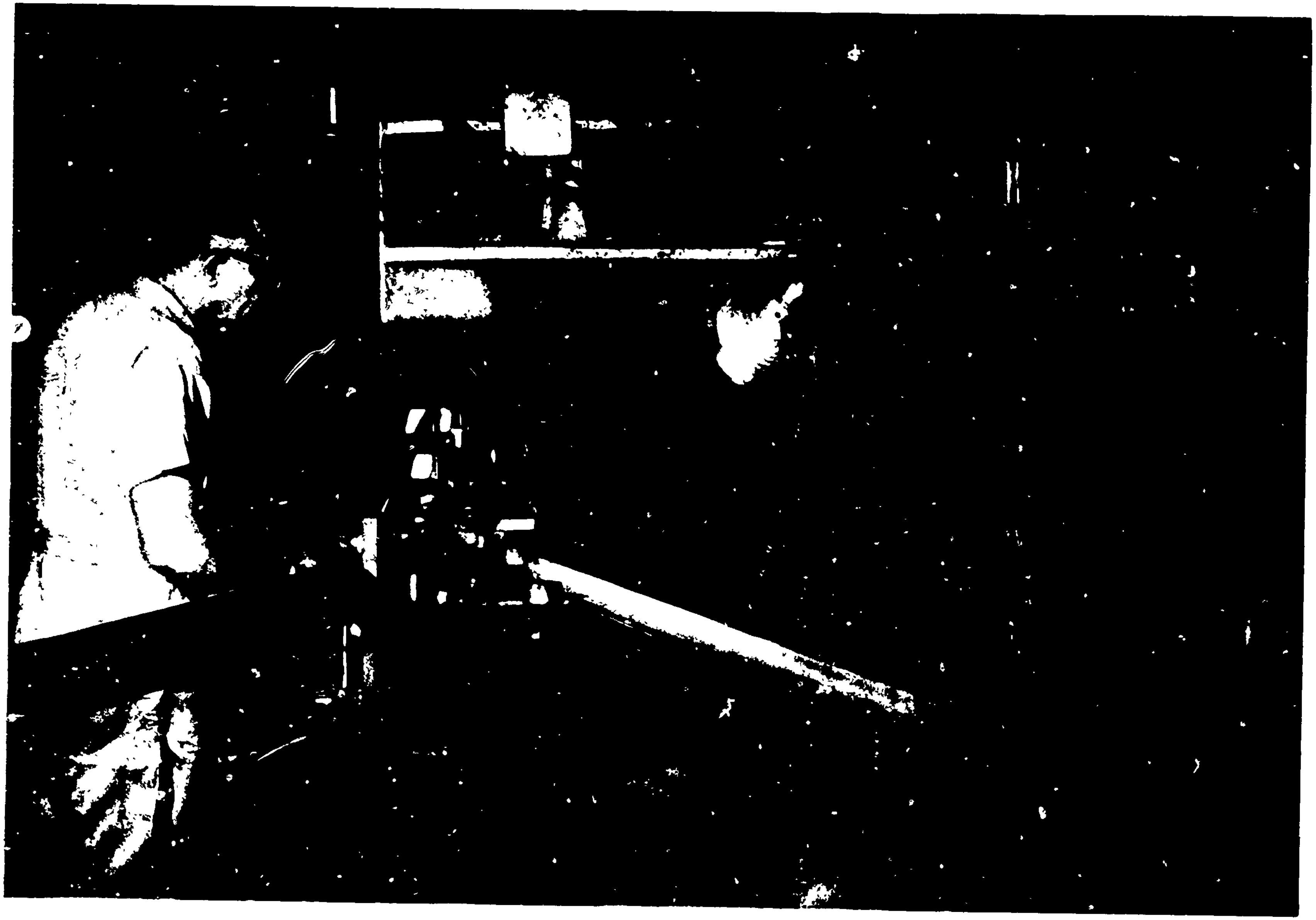


FIG. 2-16- 20-FT. LONG EXTRUDED "T" ON THE RIGHT AND THE FLAT SHEET ON THE LEFT AS THESE ELEMENTS ARE GUIDED INTO THE WELDING STATION BY TOOLING SET TO MAINTAIN A 7° VEE IN THE WELDING AREA

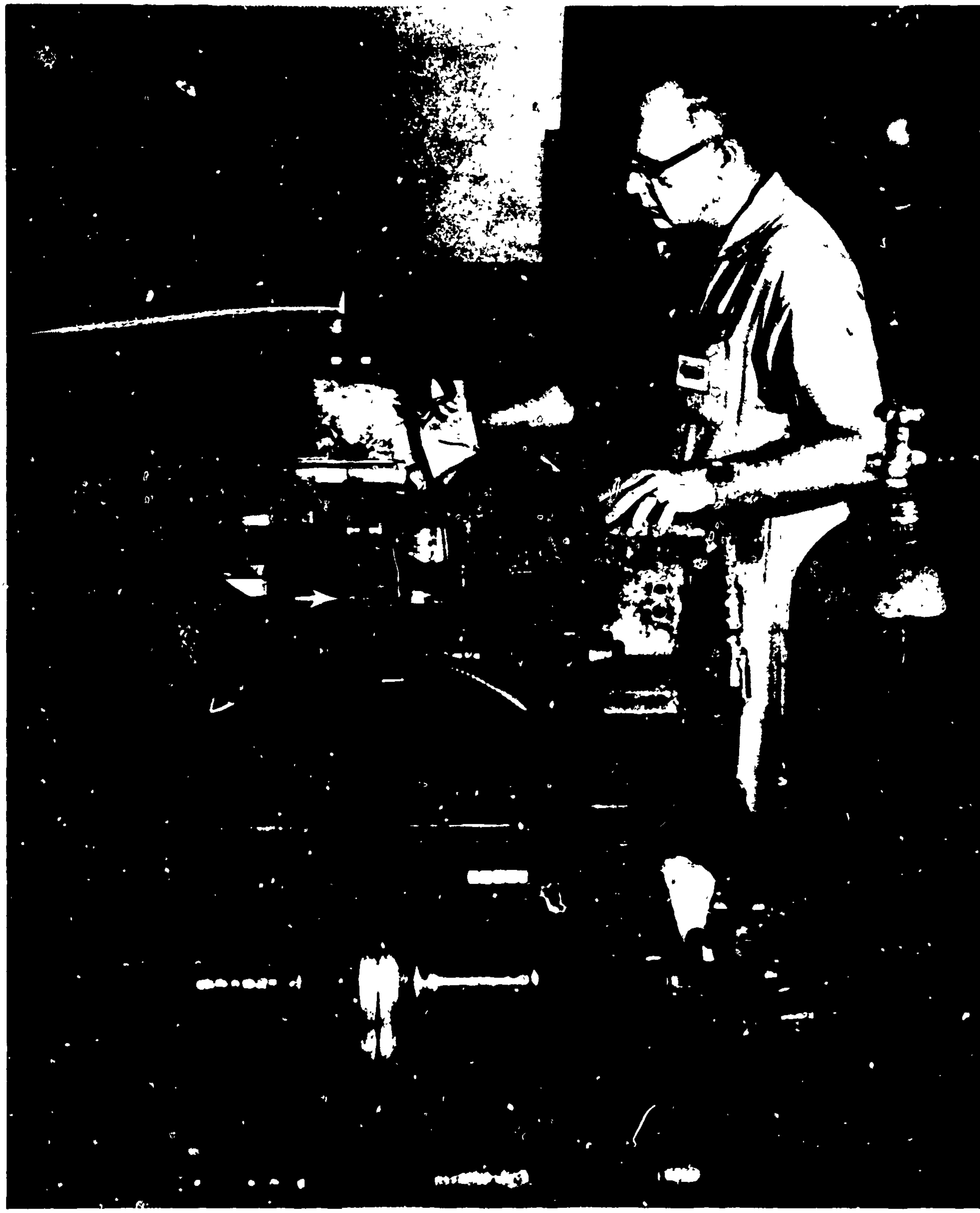


FIG. 2-17- DOWNSTREAM VIEW OF THE WELDING STATION SHOWING TWO OPPOSING SQUEEZE ROLLS AND SMALL GUIDE ROLLS RIDING ON THE LEG OF THE EXTRUDED "T" SECTION (NOTE THE ''ELD JOINT ABOUT 1 FT. DOWNSTREAM FROM THE SQUEEZE ROLLS. THE PULL-OUT ROLL DRIVE STAND IS IN THE FOREGROUND.)

FIG. 2-19- TYPICAL SECTION OF A TRIAL WELD SHOWING "STITCHING"

The flat sheet is shown on the bottom of the picture and the extruded "T" on the top. There was excessive melting on the "T" but almost no melting on the flat strip. Resulting "weld had very low strength."

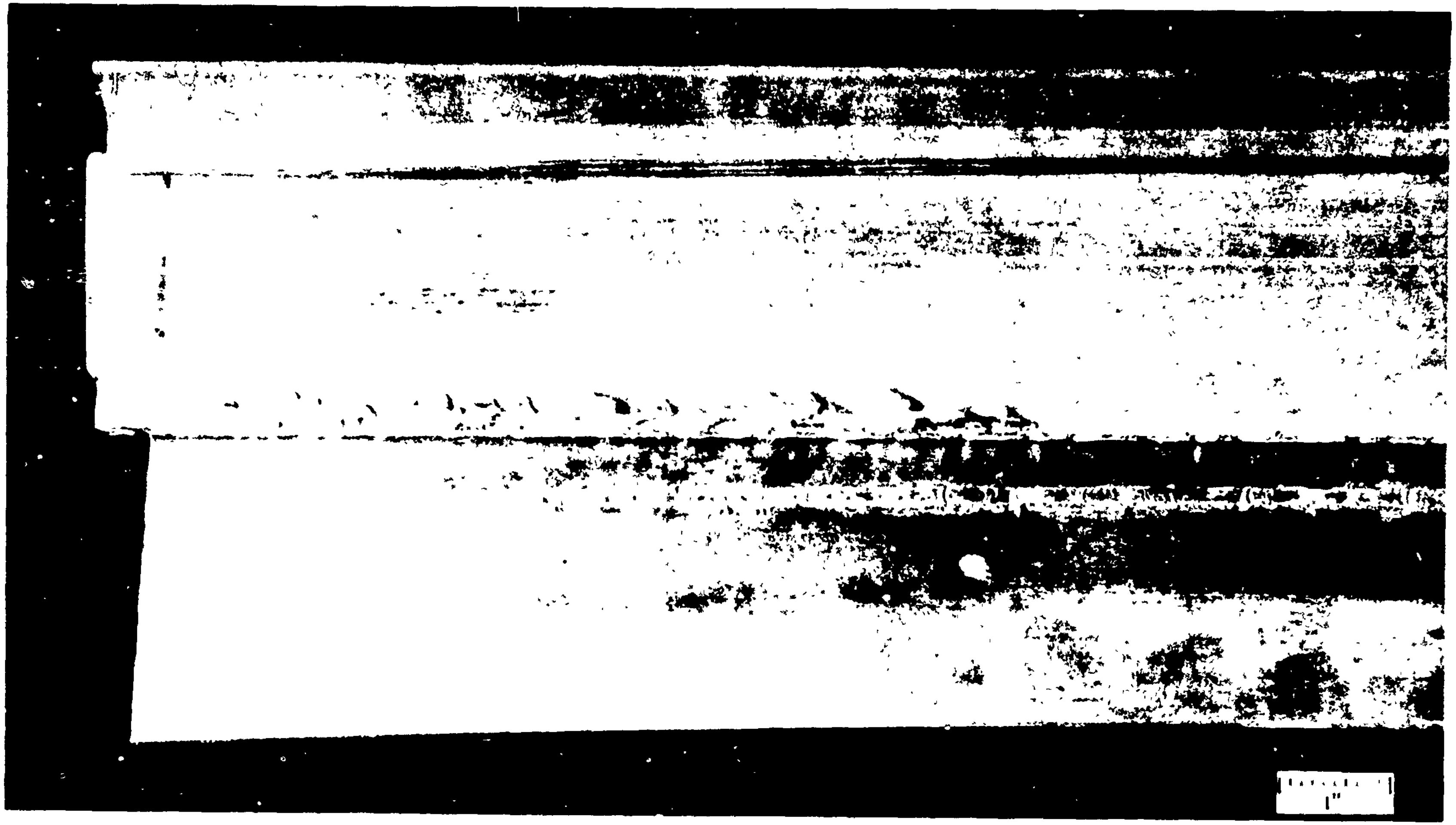


FIG. 2-20- SECTION OF TRIAL WELD MADE AT HIGH CURRENT SETTING - 480 Δ

In this case, considerable melting occurred on the flat sheet. An excessive amount of melting was present on both pieces. This produced "stitching" as shown but it also produced a weld with quite high breaking strength.

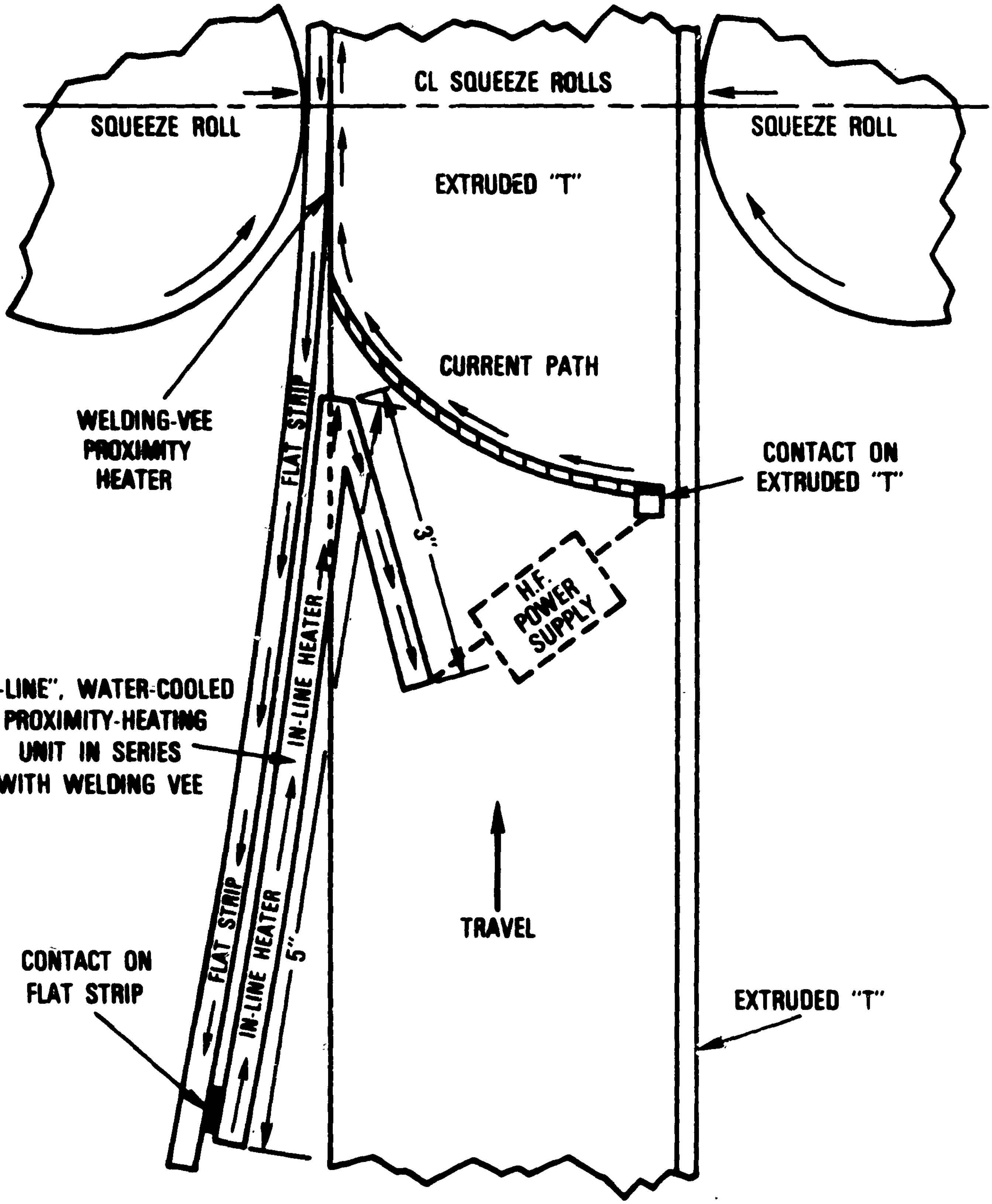


FIG. 2-21- PATH OF CURRENT DURING ONE CYCLE, FROM CONTACT ON "T" TO WELDING VEE, TO CONTACT ON SHEET AND BACK TO POWER SOURCE THROUGH WATER-COLD SIDE OF THE "IN-LINE" PROXIMITY HEATER.

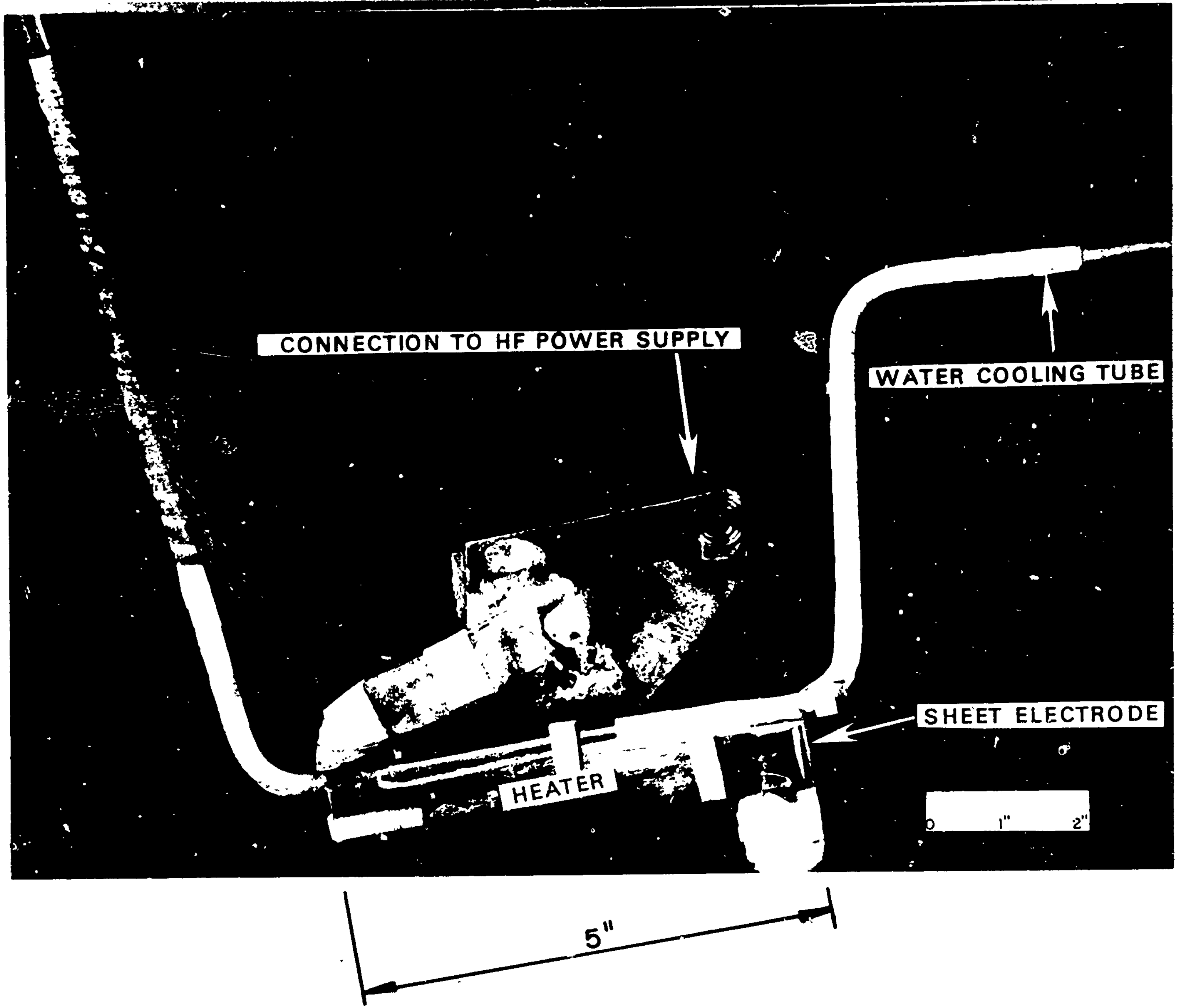


FIG. 2-22- VIEW OF THE IN-LINE HEATER FROM SHEET ELEMENT SIDE.

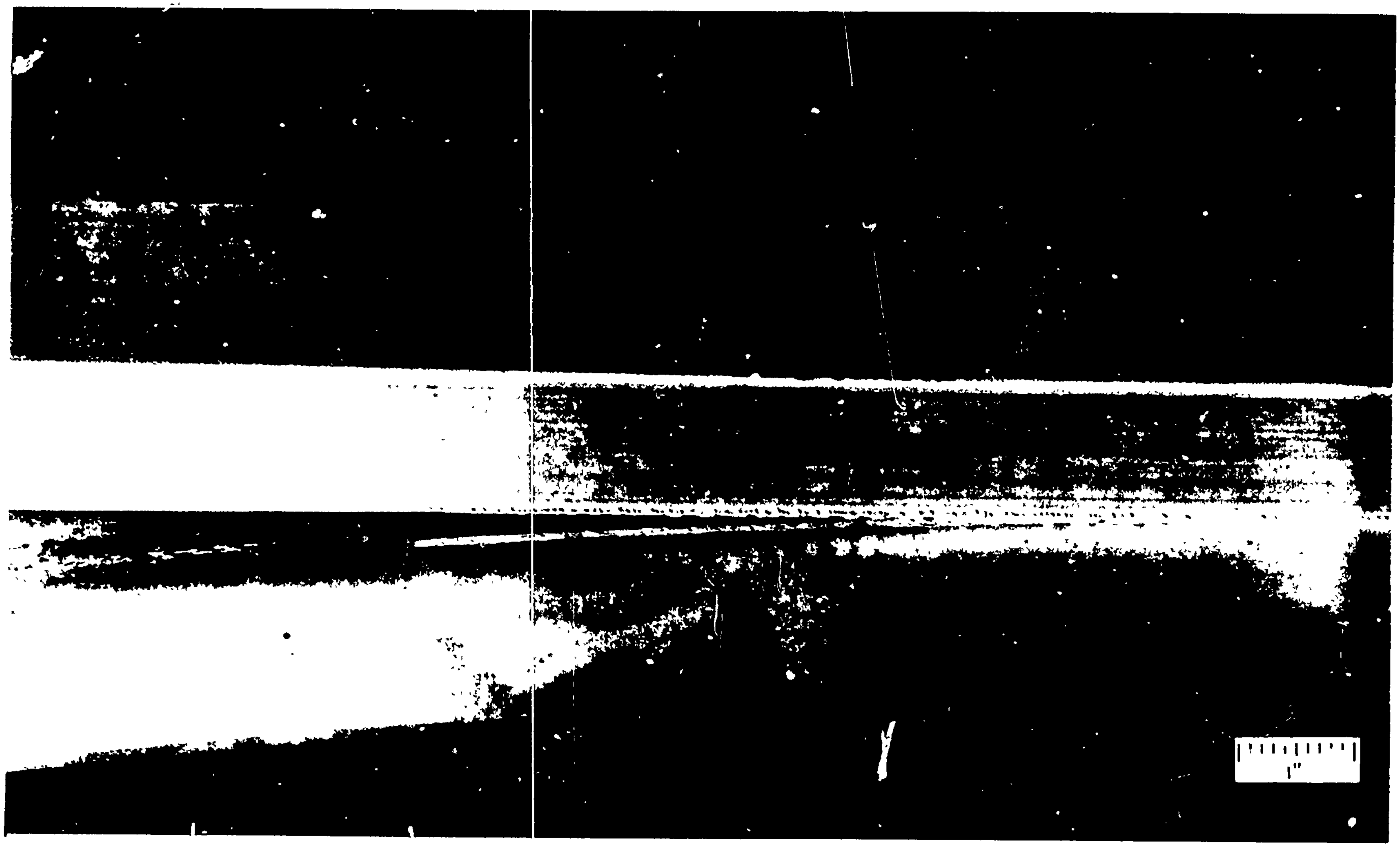


FIG. 2-23- WELD MADE USING IN-LINE HEATER ON SHEET.

Note: Relatively low amount of heating on the stem side of the Vee, and small amount of extruded metal. Especially note lack of stitching and clean area on the sheet where the weld was pulled away. A good heating pattern was obtained.

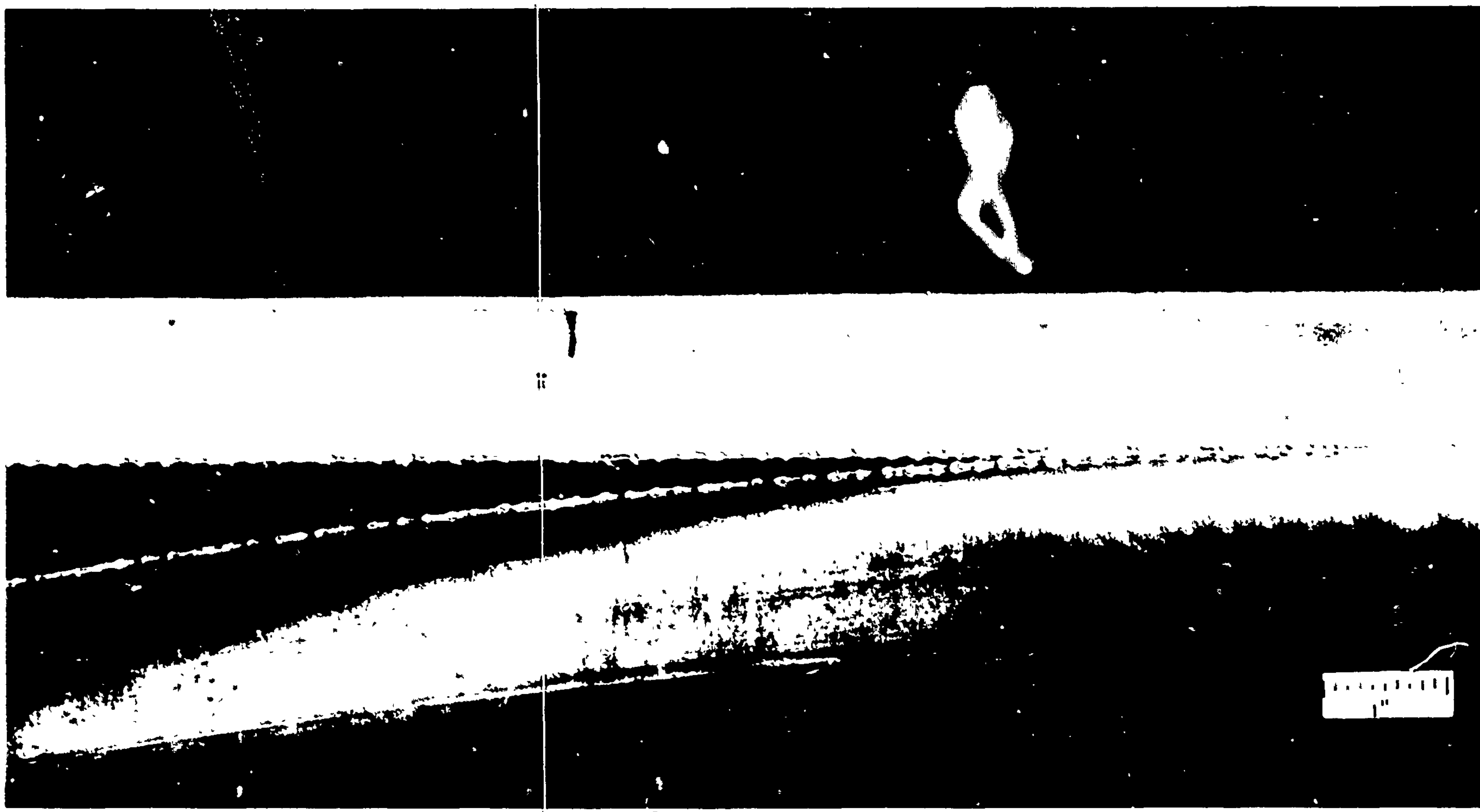


FIG. 2-24- TYPICAL SECTION OF WELD (PULLED APART) MADE WITH HIGHER POWER INPUT AND THE SAME GENERAL CONDITIONS OTHERWISE NOTED ON THE WELD SHOWN IN FIG. 2-23.

Note: Stitching of weld.

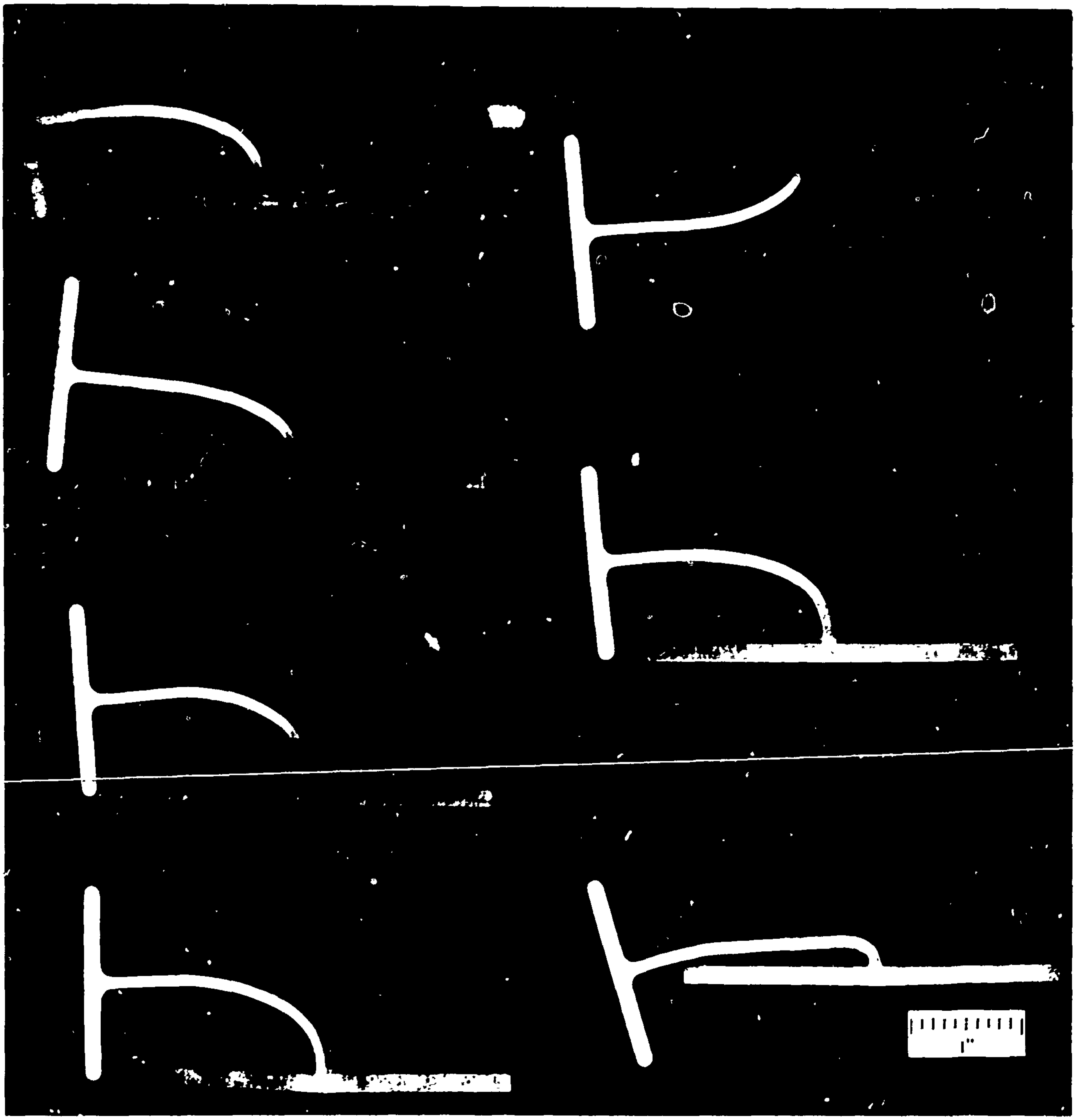


FIG. 2-25- TYPICAL SIDE BEND TESTS OF WELDS MADE WITH 400°F PREHEAT OF SHEET AND IN-LINE HEATER

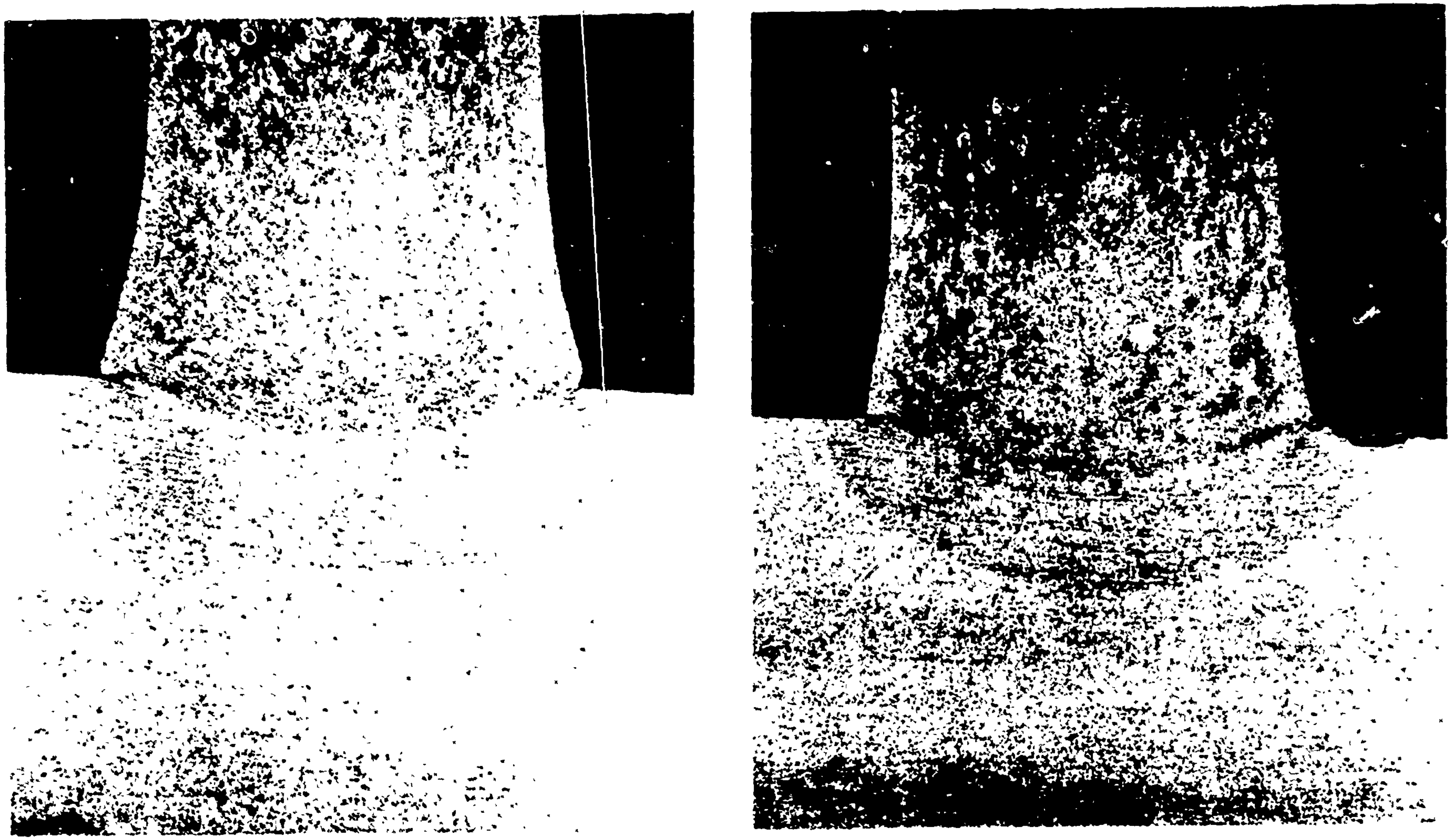


FIG. 2-26- TYPICAL CROSS SECTIONS OF HIGH-FREQUENCY RESISTANCE WELDS MADE WITH IN-LINE HEATER AND 400°F PREHEAT OF SHEET

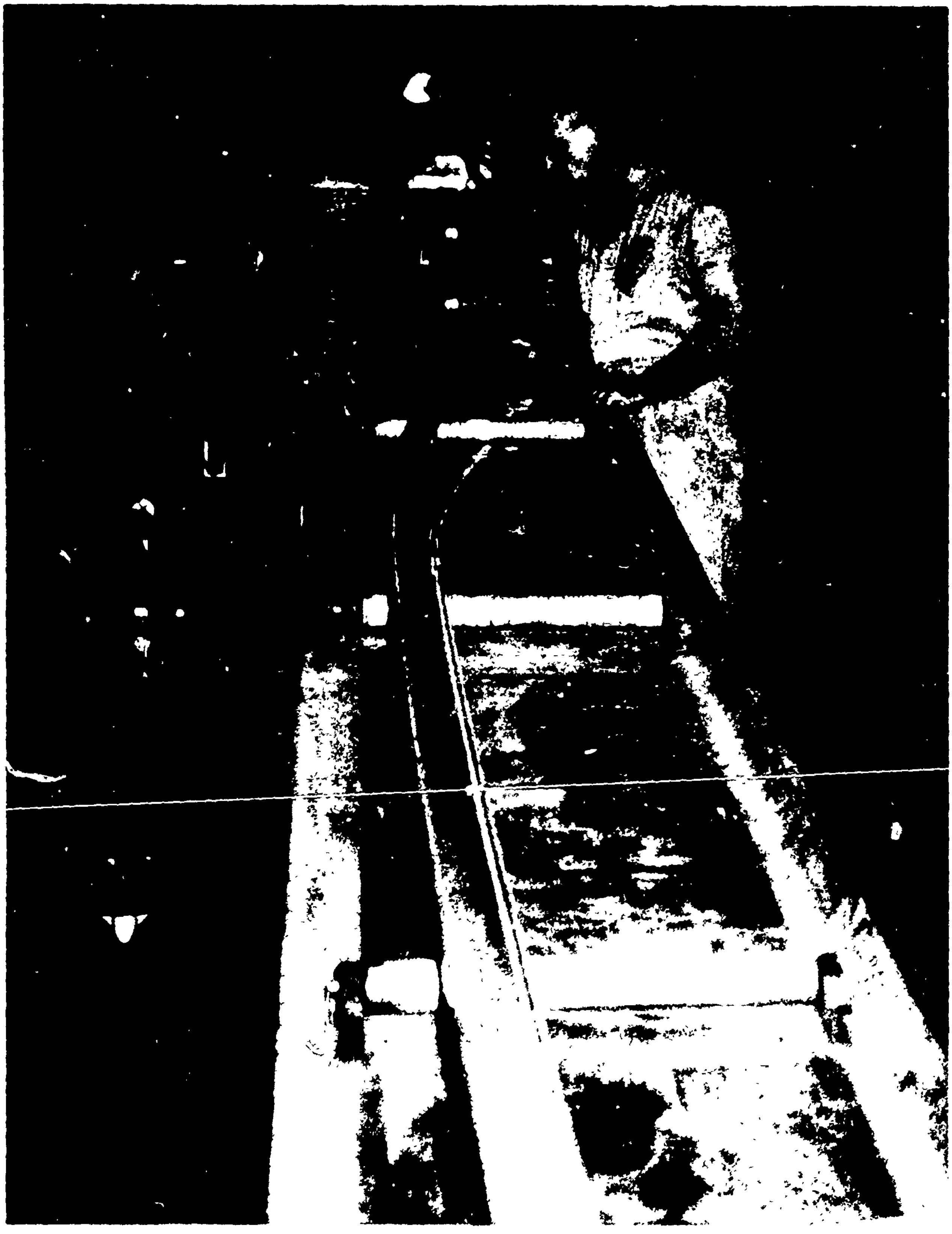


FIG. 2-27 WELDED "T" STIFFENED PANEL ON RUN-OUT TABLE

The relatively straight section of the foreground was not preheated. The remainder is that part which was preheated to 400°F.

2.1.4 Explosion Welding - Explosion welding of the aluminum "T" shaped 5456 extrusion to the 5456 sheet material was conducted by the Battelle Columbus Laboratories. The specimen required for evaluation was welded in 4' lengths using the 5456-H111 3" high "T" extrusion with a 1/8" web being joined to the center of the 4" wide 3/16" thick 5456-H116 sheet. (See Figure 1-1).

2.1.4.1 Welding Equipment and Fixturing - All explosion welding was conducted by Battelle in their concrete explosion structure capable of containing the explosion shock wave and noise. In addition to the concrete chamber, nearby explosive storage bunkers and an area for cleaning and assembling of parts to be welded are necessary. Throughout the program, Trojan-US Powder Company explosive SWP-1, which is a powder explosive with a detonation velocity of 3,000 meters per second, was utilized. Since the type of tooling and fixturing and its arrangement are part of welding parameters, the various fixtures used for this explosion welding study will be included in the discussion on welding the various specimens.

2.1.4.2 Initial Evaluation of the Weldability of 5456 Aluminum - These initial weldability trials were performed on a simple 5456 specimen consisting of two pieces of 3/16" thick 5456-H116 sheet 2" wide by 8" long. The sheet surfaces were welded to each other to form a 2" by 8" by 3/8" thick assembly. (See Figure 2-28). These trials were conducted using a fixed explosive thickness of 1/2" (1.23 grains per square centimeter while the width was varied from 1 to 1-1/2" and the uniform standoff distance was varied from 1/8 to 3/16"). Utilizing metallographic sectioning and attempting to separate the aluminum sheets by chiseling showed that of the 6 weld trials performed, the optimum explosion welding parameters of 1/2" thick by 1-1/2" wide explosive charge using a uniform 1/8" standoff distance produced the highest quality weld that could not be separated by chiseling. Figure 2-29 shows a small wave shape bond characteristic of the weld resulting from the optimum parameters listed above. Figure 2-30 shows a larger wave shape bond with voids and cracks obtained using the same explosive charge with a uniform 3/16" standoff distance. This indicated that the use of excessive collision energy between the two pieces to be welded, resulting from excessive explosive charge or excessive standoff distance, will produce microcracking in the weld interface which will be detrimental to the properties of the weld. Transverse microhardness surveys of the samples revealed some increase in the hardness of the 5456 alloy during welding. This hardness increase due to cold work appeared to be greater in the cladding component (flyer plate), vary in the base component (base plate).

2.1.4.3 Development of Welding Parameters and Tooling - The development of the explosion welding parameters and the support tooling to achieve a sound weld in the "T" stiffened panel configuration (Figure 1-1) employed a 12" long "T" extrusion and sheet. Tooling is required to provide support to the thin 1/8" web of the "T" during welding period. In this method of fabrication, the 3/16" thick 5456 sheet (flyer plate) is propelled against the 1/8" wide end of the web of the extrusion (base plate). Using the proper explosive charge and standoff distance between the flyer plate and the base plate will yield the proper kinetic energy and collision to produce jetting (essential for surface cleaning action) just ahead of the impact and the resultant welding of the flyer to base plate.

The first assemblies attempted employed solid steel bar tooling and the optimum welding parameter described in paragraph 2.1.4.2. Figure 2-31 shows the specimen and tooling setup for this trial. This combination of tooling and parameters produced no jetting on the surface and no resultant weld between the "T" extrusion and the sheet. This indicated that the collision energy was being absorbed by the interface between the extrusion leg and the steel tooling.

The explosive charge and standoff distance were increased in subsequent tests. Jetting and welding were achieved as evidence by the metal transfer between sheet and extrusion; however, the weld had been fractured by the rebound of the flyer plate immediately following welding due to its acoustical mismatch with the steel tooling. The narrow web and resultant narrow weld (1/8") could not tolerate the rebound forces thus resulting in the tensile failure of the weld.

In order to change the characteristics of the weld specimen and tooling, an experiment was conducted to evaluate the possible techniques for eliminating the rebound phenomena. Figure 2-32 describes the welding assembly utilizing 1/4" 6061-T6 aluminum strips which were positioned in contact with and on both sides of the stem of the "T" component. Steel support bars were then positioned on the outside surfaces of the quarter inch strips. In addition, a 3/16" thick 5456 aluminum plate was positioned between the explosive charge and the flyer plate to serve as a momentum trap to the rebound of the flyer plate. The explosive charge was increased to 5/8" thick and 2-1/2" wide and the standoff distance was increased to 3/16" in order that the experiment may accommodate the increased thickness of the moving component.

This arrangement of specimen and tooling produced about 3" of weld in a 12" length. It did not reduce the rebound fracturing of the weld sufficiently in the flyer plate sheared at the junction between the aluminum side plates and the steel support bars.

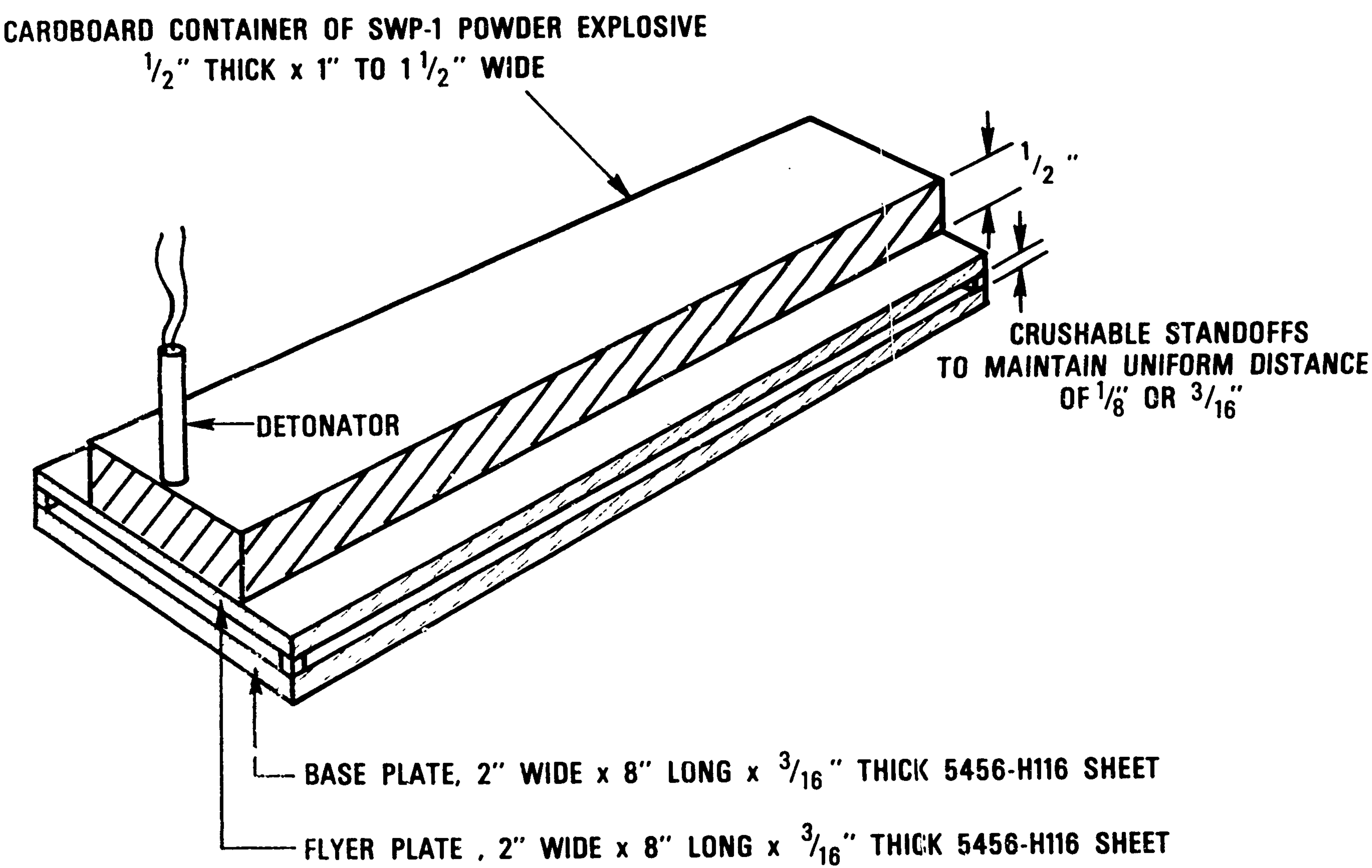
Based on these results, it was decided that due to its unfavorable rebound characteristics in conjunction with aluminum, steel tooling should be completely eliminated and replaced with all aluminum tooling. In order to prohibit welding of the aluminum bar tooling to the flyer plate, sacrificial parting strips of 0.050" thick 6061 sheet were inserted adjacent to the web of the extrusion. These parting strips became welded to the flyer plate, but did not weld to the web of the extrusion (Figure 2-33). Trials to keep the strips from welding to the flyer plate were unsuccessful. The effect on the evaluation of the welded assemblies was judged to be limited to slightly increasing the stiffness of the flyer plate portion. Therefore, extensive trials to eliminate the welding of the strips to the flyer plate were not undertaken. The use of the 3/16" 5456 momentum trap plate was continued since it also reduced the weld distortion of the flyer plate. While this arrangement described in Figure 2-34 resulted in considerable improvement in welding, there were still indications of rebound and movement in the solid aluminum tooling to cause some fracturing of the narrow 1/8" width of weld. This indicated that while the tooling must provide support to the stem during the welding operation, it must immediately move out and away from the welded members so that it cannot rebound and strike the flyer plate afterwards.

A fourth tooling arrangement was therefore evaluated in the next series of the experiment. This arrangement involved positioning of 1-1/2" by 1-1/2" 6061 tooling bars, with the 0.050" thick aluminum sacrificial parting strips laminated as before on the top surface against the upper portion of the web of the "T" as shown in Figure 2-35. The "T" component with its support tooling was then positioned in water which came to within a 1/4" of the top of the stem or the welding surface. It was expected that this arrangement would provide sufficient support for the web than the flyer plate during welding. Immediately after welding, however, the water would allow the tooling bars to move down and outward from the web and the flyer plate without the rebound that had been causing the failure of the weld in the previous experiments. This experiment was again conducted with the 5/8" by 2-1/2" explosive charge with a 3/16" standoff distance. Excellent welding was achieved between the flyer plate and the web with the exception of the normal unbonded areas approximately 2" long at the beginning and trailing ends of the specimen. One inch long sections from the welded specimens were subjected to side bend tests in which the flyer plate portion was gripped in a vice and the "T" component was bent over by hammering. The welds did not fail in these tests. In order to evaluate the successful support system utilized on the 12" specimen, an intermediate scale-up of experiment was then conducted with a 2-foot long sample utilizing the same support and explosive welding parameters as had been used to the small specimens. The sample was found to be successfully welded with the exception of the expected leading and trailing end unbonded regions.

<u>2.1.4.4 Welding of the 4' Long "T" Stiffened Panels for Evaluation</u> - The first welding trial on the 4' long assembly employed the tooling and welding parameters shown to be successful in the 2' long welding trials. Figures 2-35, 2-36 and 2-37 show the tooling and specimen assembly employed for these welds. The initial weld revealed an 18" long section in the center portion of the specimen to be unbonded. Sectioning and examination of the unbonded weld surfaces further revealed evidence of gross underwelding. An additional experiment demonstrated that this underwelding was a result

of precursor stress waves causing movement of the components ahead of the welding front and improper fit-up of the aluminum support tooling bars against the web of the "T" component. The third experiment was conducted in which two modifications were made to the setup for welding. Instead of a constant 3/16" standoff distance, an angle standoff was employed which varied from 0.15" at the beginning to 0.25" at the trailing end. In addition, two adjacent surfaces of the aluminum tooling bars were machined to provide flat surfaces for uniform contact and support against the web and under the thin sacrificial parting strips on the welding surface. These modifications resulted in a weld over the full length of the "T" stiffened panel with the exception of a 3" long unbonded section at either end.

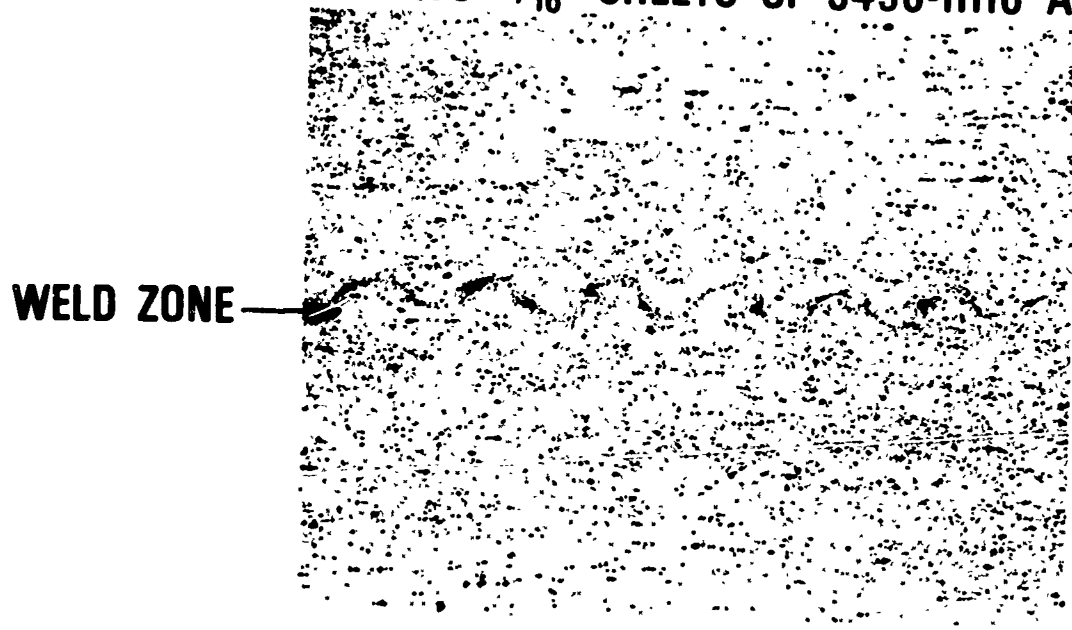
A final series of five 4' long "T" stiffened specimens were prepared for welding using the assembly shown in Figure 2-35 with the exceptions of the angle standoff distance and the machined plate described in the paragraph preceding. Of the five specimens tried, four were found to be completely welded while the fifth had an unbonded area in its central portion approximately 13" long. Examination of this unbonded section revealed that it had been welded but that the weld had failed indicating that some potential for weld failures still existed with the narrow weld, even with the extensive modifications to the tooling described in Paragraph 2.1.4.3. The four completely welded "T" stiffened panels were submitted for evaluation, examination and testing.



SPECIMEN ASSEMBLY FOR EVALUATION OF EXPLOSION WELDABILITY OF 5456 ALUMINUM ALLOY

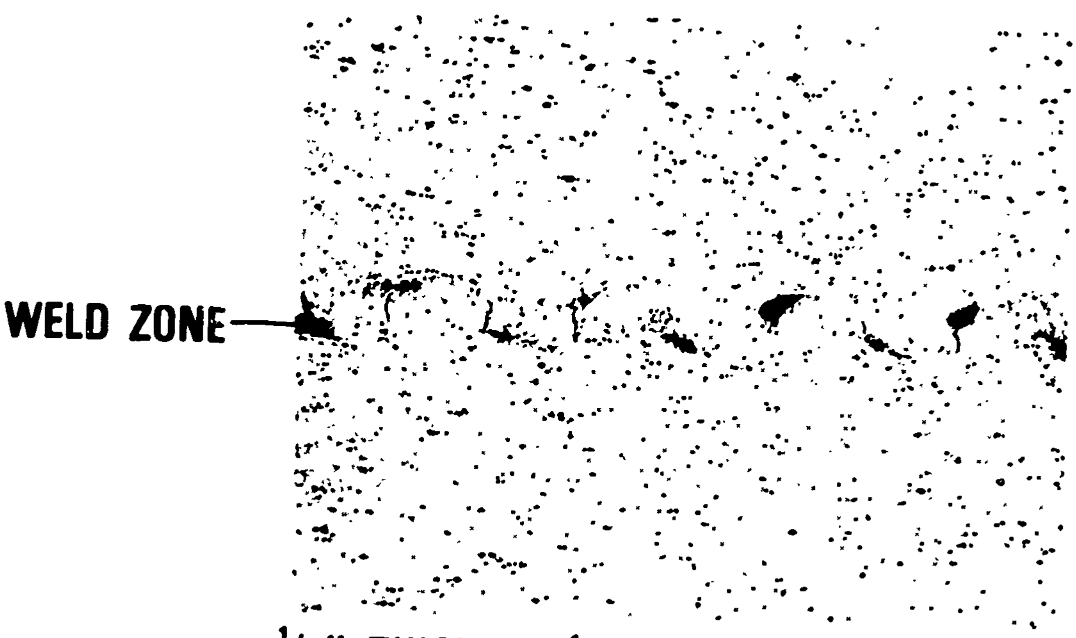
FIG. 2–28

METALLOGRAPHIC SECTIONS OF EXPLOSION WELDS BETWEEN TWO 3/16" SHEETS OF 5456-H116 ALLOY



1/2" THICK × 1 1/2" WIDE SWP-1 CHARGE, 1/8" STANDOFF DISTANCE (100X) OPTIMUM PARAMETERS

FIG. 2–29



1/2" THICK × 1 1/2" WIDE SWP CHARGE, 3/16" STANDOFF DISTANCE (100x) OVERWELDED - VOIDS & CRACKS

FIG. 2–30

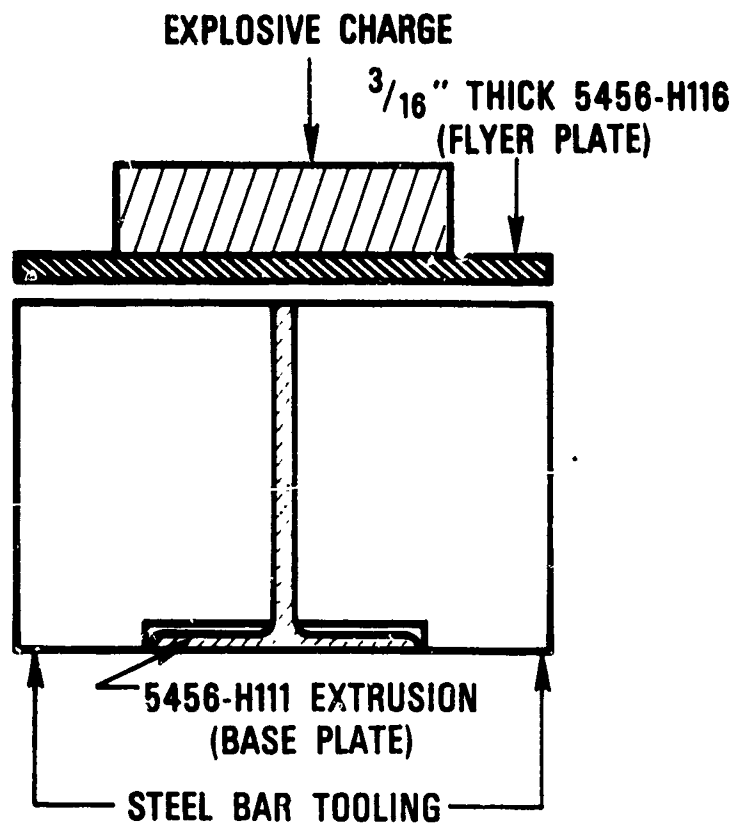


FIG. 2–31

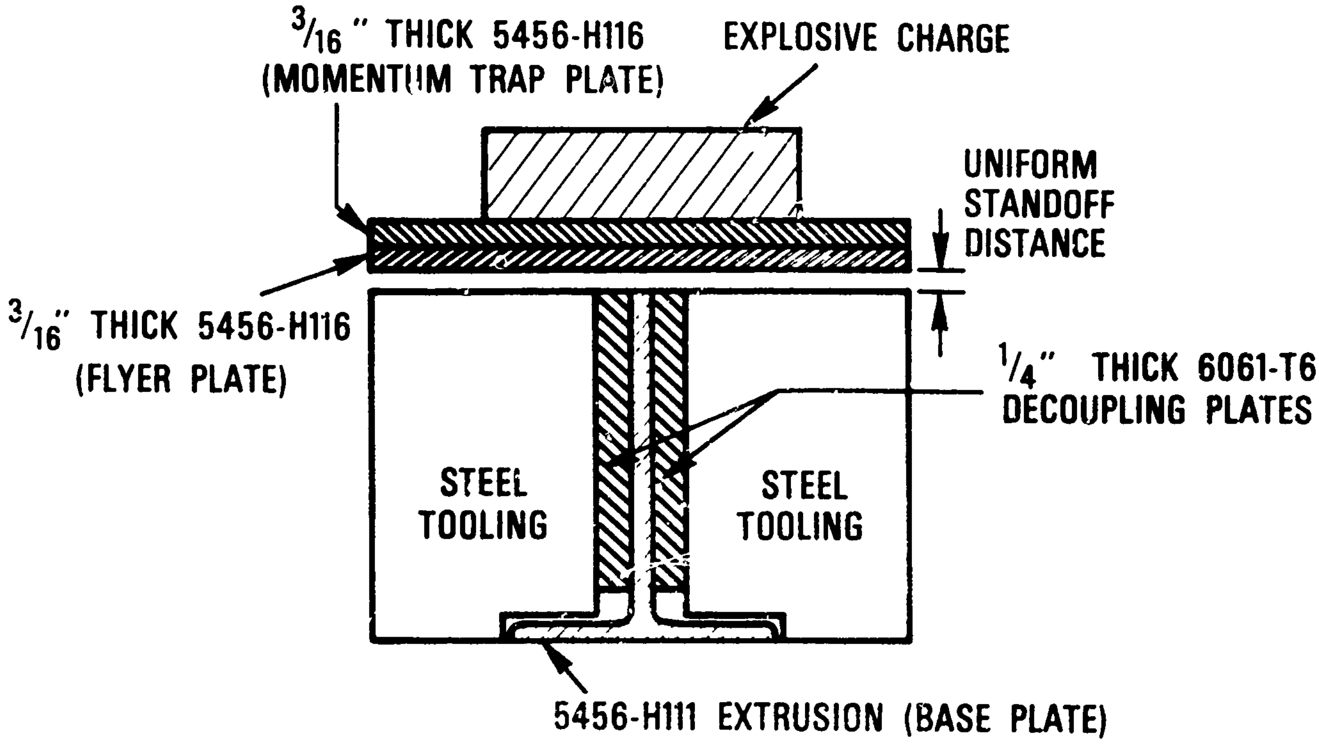
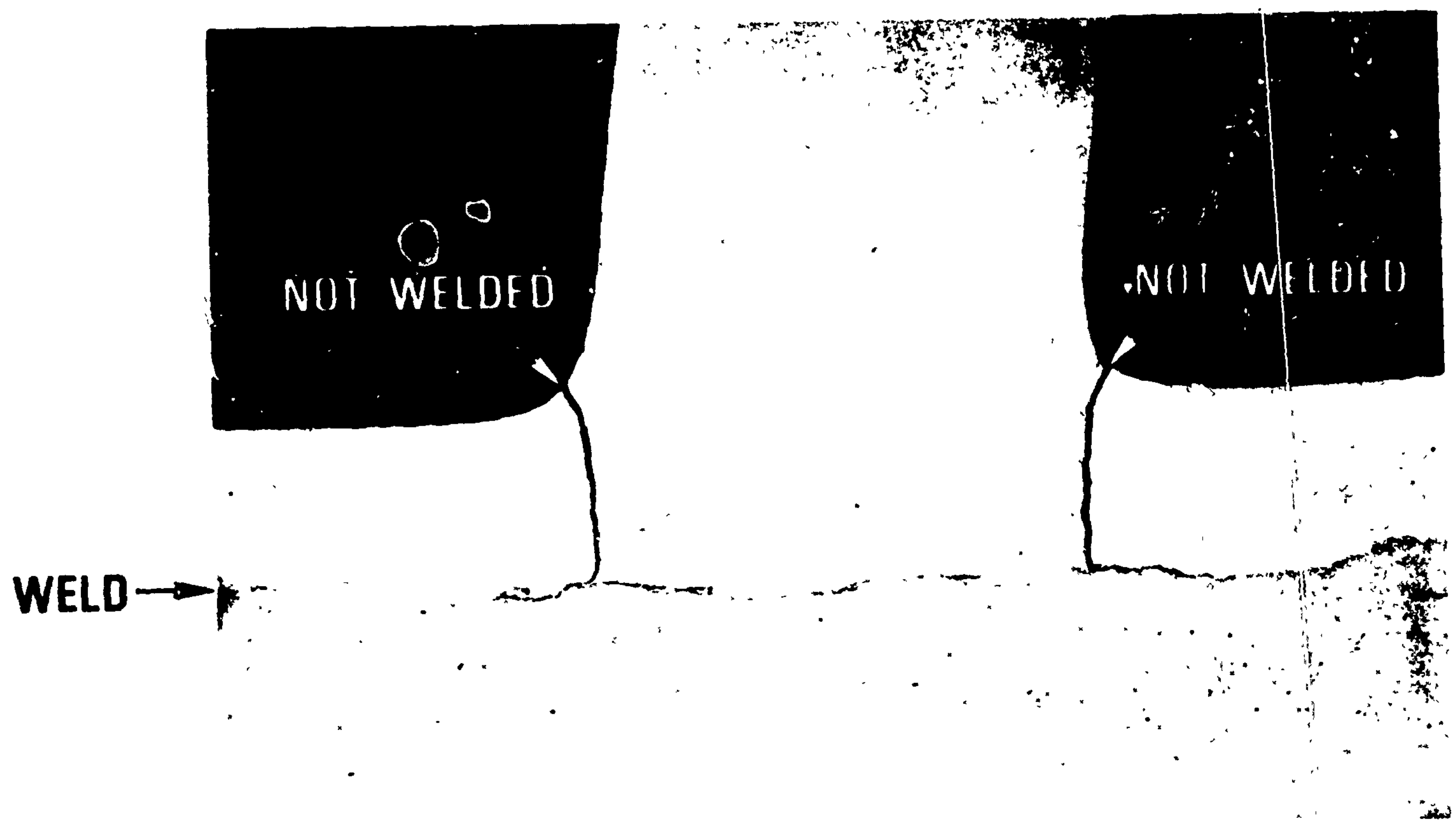


FIG. 2–32

ASSEMBLY FOR EXPLOSION WELDING



METALLOGRAPHIC SECTION SHOWING WELD BETWEEN EXTRUSION LEG AND PARTING STRIPS AND THE $^3/_{16}$" THICK 5456-H116 SHEET

FIG. 2—33

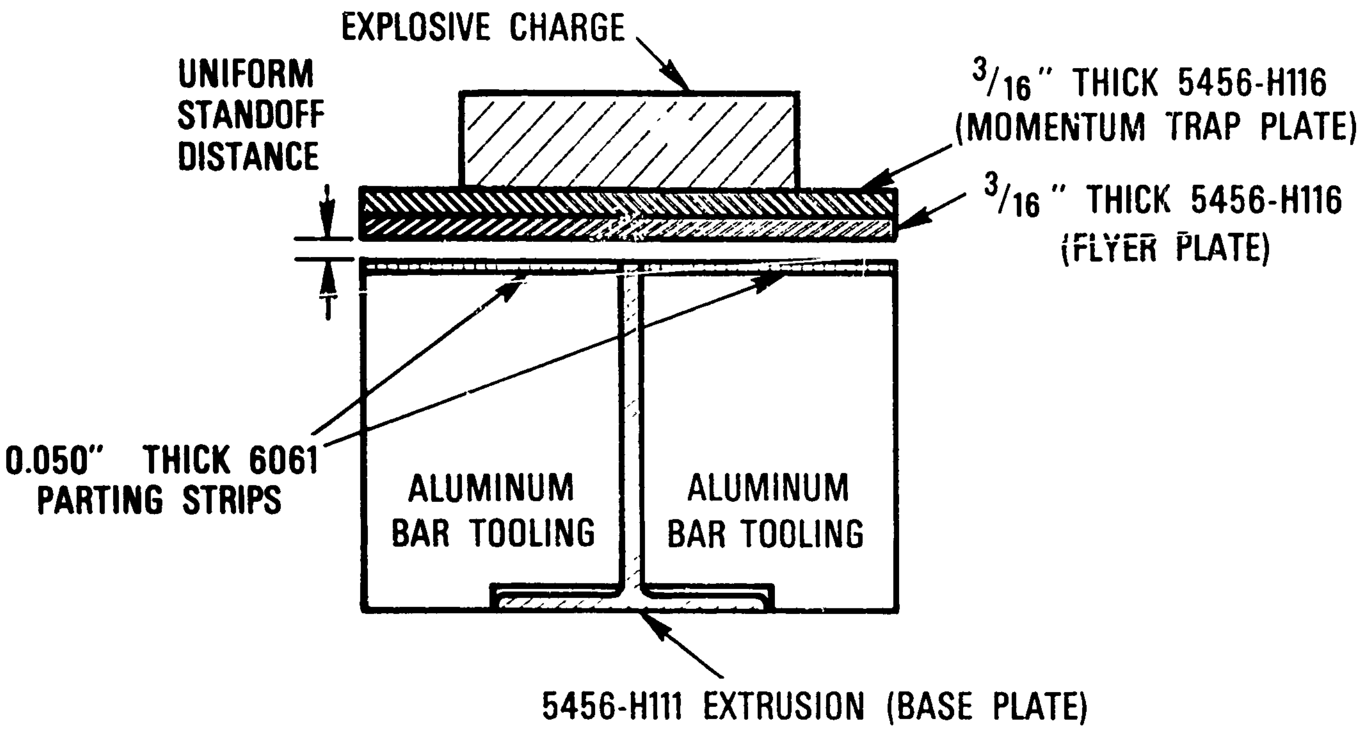


FIG. 2–34

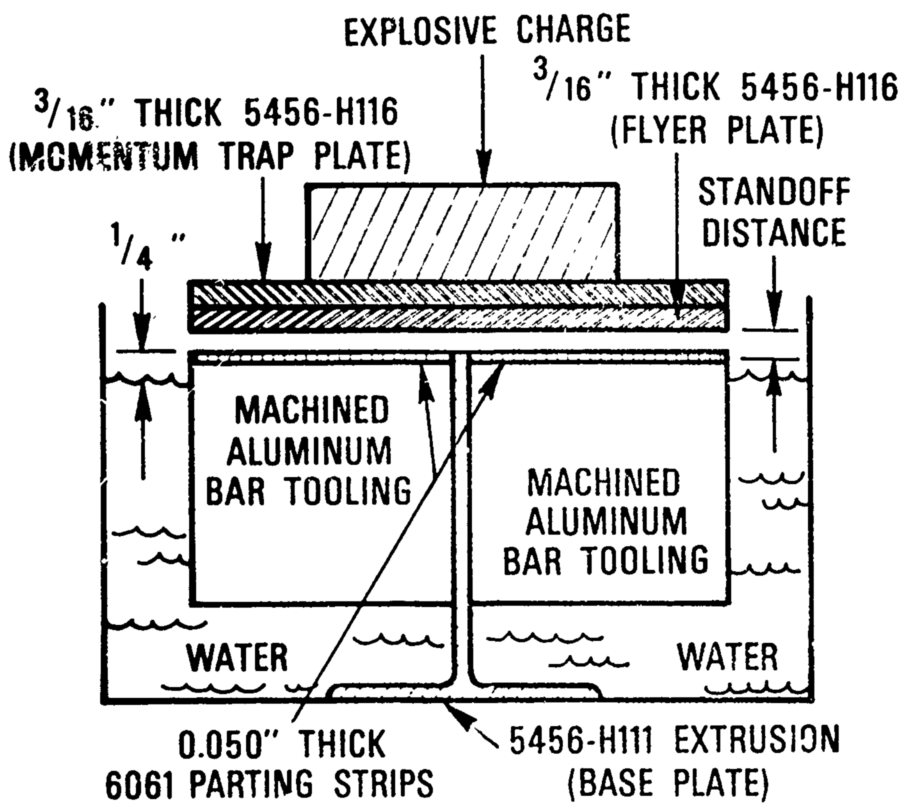
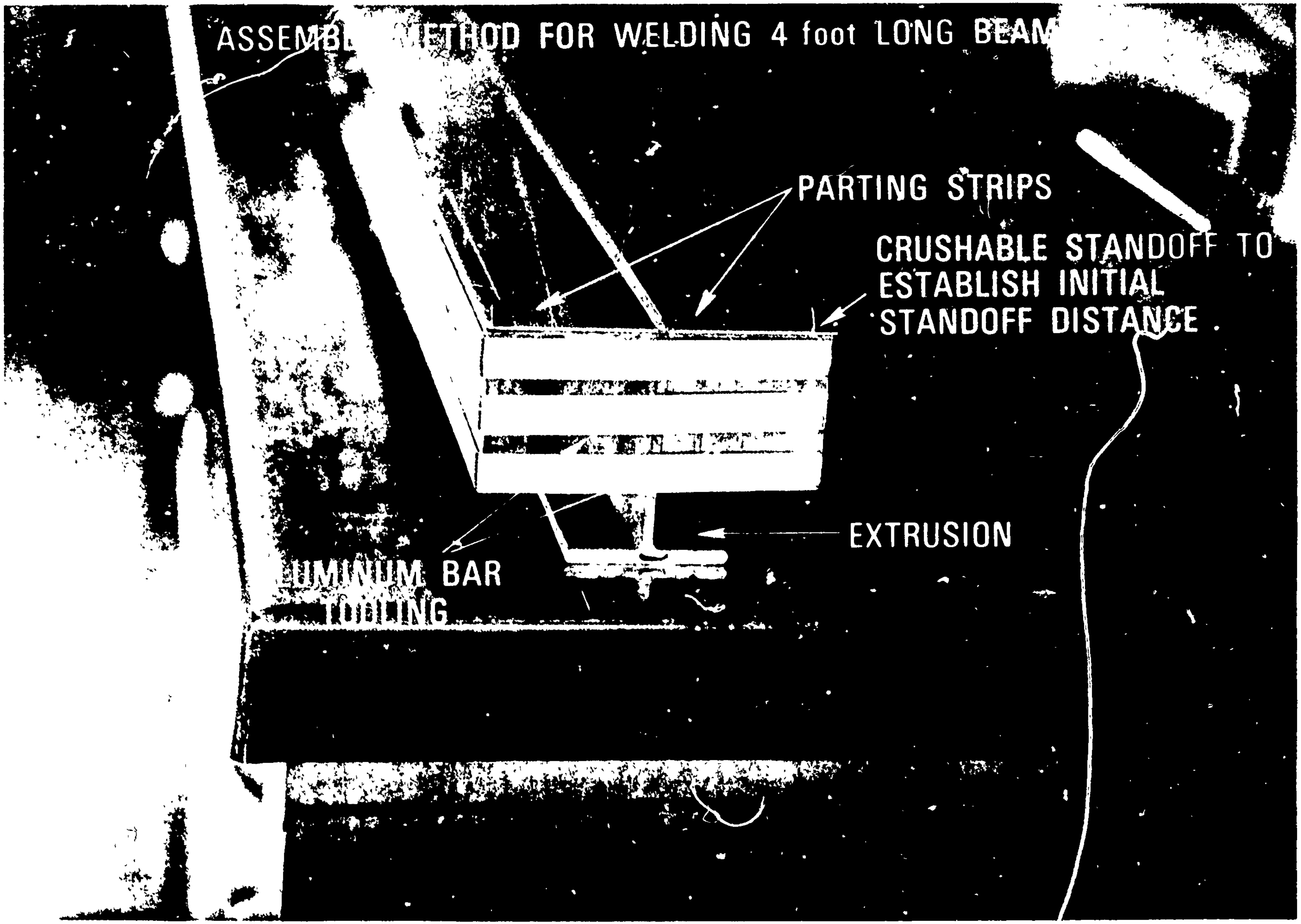


FIG. 2–35

ASSEMBLY FOR EXPLOSION WELDING



FLYER PLATE, MOMENTUM TRAP PLATE AND EXPLOSIVE CHARGE OMITTED

ASSEMBLY READY FOR EXPLOSION WELDING

FIG. 2—37

2.1.5 In Chamber Electron Beam Weldtrusion - All in chamber electron beam weld development was done at Babcock & Wilcox Research Center, Alliance, Ohio. Alcoa saw cut all material to size, cleaned (caustic etch) and supplied all of the material to be welded. Babcock & Wilcox was subcontracted to design and fabricate a welding fixture, develop welding parameters, and fabricate all electron beam weldtrusion panels.

Aluminum "T" shaped extrusions (5456-H111) with a 2" flange and 3" leg were welded to 3/16" 5456-H116 aluminum sheet. Welding was done from the blind side such that the weld penetrated through the 3/16" sheet into the leg of the extrusion. This is commonly referred to as the "Weldtrusion" technique. A photomacrograph is shown in Figure 4-22.

2.1.5.1 Equipment and Fixture - Babcock & Wilcox has an ERI (now Union Carbide) electron beam welder (see Figure 2-38). The unit is equipped with a 45 kilowatt power supply and chamber dimensions of 68" x 68" x 78". The system has the added capability of either using a soft or hard vacuum during the welding process. Additional options that the equipment has are listed below:

1. Movable Gun - Either horizontal or vertical directions.
2. Automatic Sequencing - Providing digital control of entire weld sequence (upslope - weld - downslope).
3. Vacuum - capable of operating at 100 microns soft vacuum, to 10^{-6} hard vacuum.
4. Electron Beam Deflection - Permits sinusoidal sweep, square wave sweep, low and high frequency circle generation.
5. Seam Tracker - Provides automatic compensation for weld joint remount or irregular weld paths of $\pm 10^{o}$ deviation from the actual weld path without operator surveillance.
6. Cold Wire Feeder - For use with .020" and .030" diameter filler additions.
7. Universal Rotary Workpiece Positioner - A universal rotary table supplied for circular and circumferential welding with a tilt through 95^{o}.

Fixturing was the most difficult part of the E.B. evaluation. Initially, inadequate clamping of the 3/16" sheet to the web of the extrusion resulted in gaps and consequently inadequate welds. Thicker hold-down bars were fabricated to allow stiffening, but this also proved to be inadequate. Finally, tabs were welded to the hold-down bars so that clamping could be obtained between the hold-down bars and the extrusion support bar. This added tooling eliminated the gapping between the extrusion and the sheet (Figures 2-39 and 2-40).

Initially, beam alignment with respect to the web was to be accomplished by aligning on a scribe mark built into the fixture. Weld metal blowout persisted due to inadequate alignment. Notches were cut into each end of the sheet material, allowing for beam alignment directly on the web of the extrusion. With the beam aligned on the web of the extrusion, weld metal blowout still persisted.

At this point, examination of the extrusion showed that the leg was not perpendicular to the flange surface. The web at the unflanged end was approximately 1/32" from the perpendicular. The edge of the web was not straight, as gaps could be seen between a level and the edge of the web.

To accommodate these variations, web braces were made. Clamping was adjusted to the web bracing so that no gaps were visible between the web and the level prior to welding. Instead of leveling the 3/16" sheet material, the web of the extrusion was leveled to be parallel with the electron beam. These fixture changes proved to be adequate to permit welding without weld metal blowout, as shown in Figure 2-41.

2.1.5.2 Basic Weld Parameters - Initial weld parameters were investigated on 1/2" 5083 plate material. However, since the heat sink of the plate was different than that encountered with the "T" stiffened panels, actual pieces had to be used for parameter development.

A speed of 100 ipm was arbitrarily selected as the welding speed. Samples were welded with various beam currents and beam deflections. These samples were cross-sectioned, etched, and visually examined for:

1. Depth of penetration in the leg
2. Freedom from defects

The final parameters were selected from those conditions showing adequate fusion and defect-free welds. It was found that a maximum beam deflection of 1/64" was tolerable to avoid bleed-through at the joint.

2.1.5.3 Final Weld Parameters - A total of thirty (30) 48" long "T" stiffened panels were welded and submitted to Alcoa. Seventeen (17) of these were submitted for evaluation of flatness and for testing. The remaining thirteen (13) weldtrusion panels exhibited blowout along the side of web. A group of these weldments is shown in Figure 2-42. Prior to welding all surfaces exposed to electron beam were cleaned by wiping with a solvent and by wire brushing.

The weld parameters used are listed below:

1. 55 kilovolts
2. 76 milliamperes
3. 100 ipm
4. 9" gun to work distance
5. Focus was 5/6" above the top of the 3/16" sheet
6. Beam oscillation - 1/64" circle diameter and a frequency of 1,000 Hz
7. Chamber pressure - 3×10^{-5} to 6×10^{-5} torr.

It was found that chamber pressure was very influential on both penetration and weld quality. Welds made at low pressure (10^{-6}) showed increased penetration but also the presence of cracks. To overcome cracking, the penetration had to be reduced. Consequently, the chamber pressure was controlled for the final beams to be in the range of 3 to 6 x 10^{-5} torr. Figure 2-43 shows an EB weld being made.

FIG. 2-38 - UNION CARBIDE (LINDE) ELECTRON BEAM WELDER USED TO MAKE EB WELDTRUSION PANELS

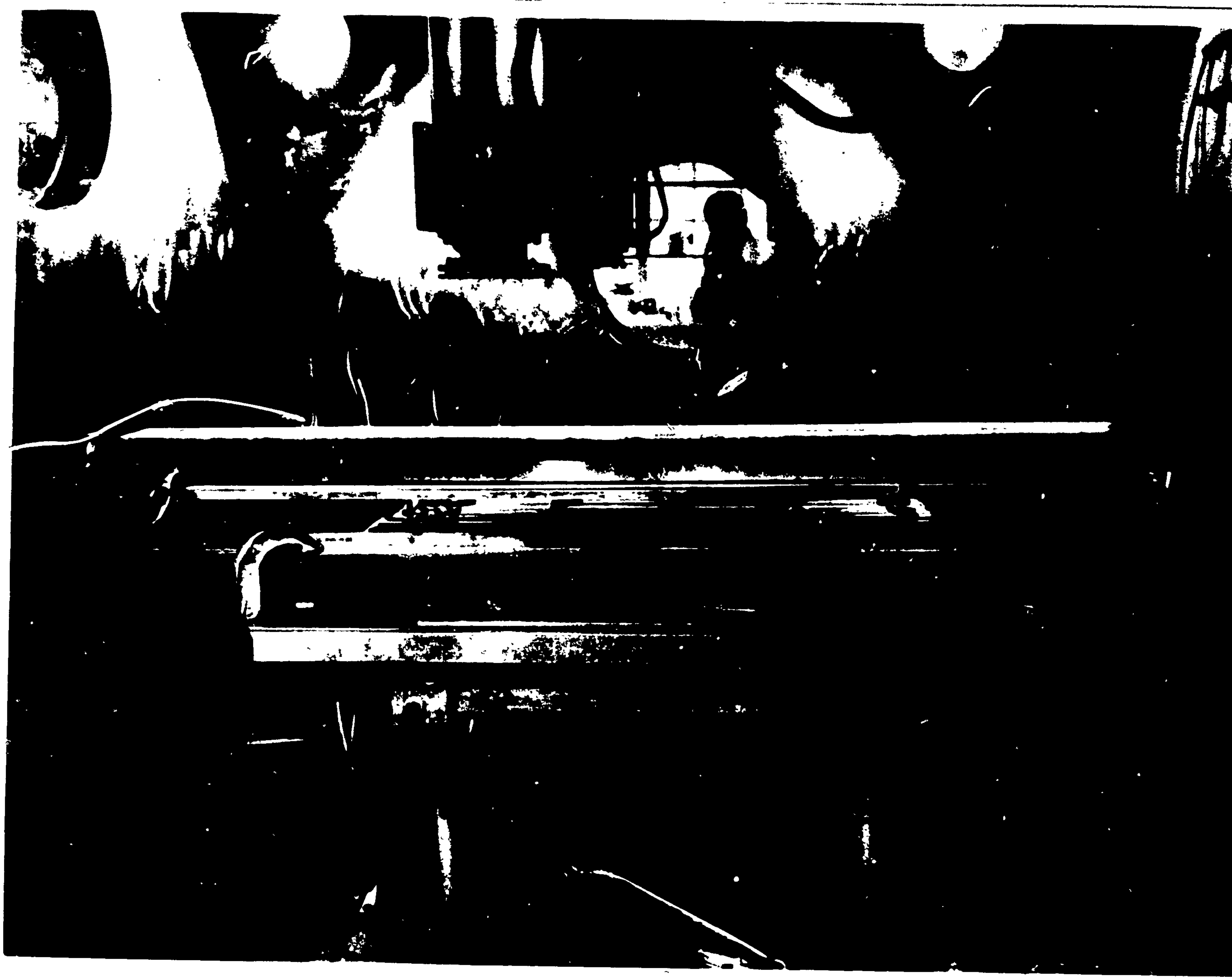


FIG. 3-30 INITIAL ELECTRON BEAM WELDING SETUP

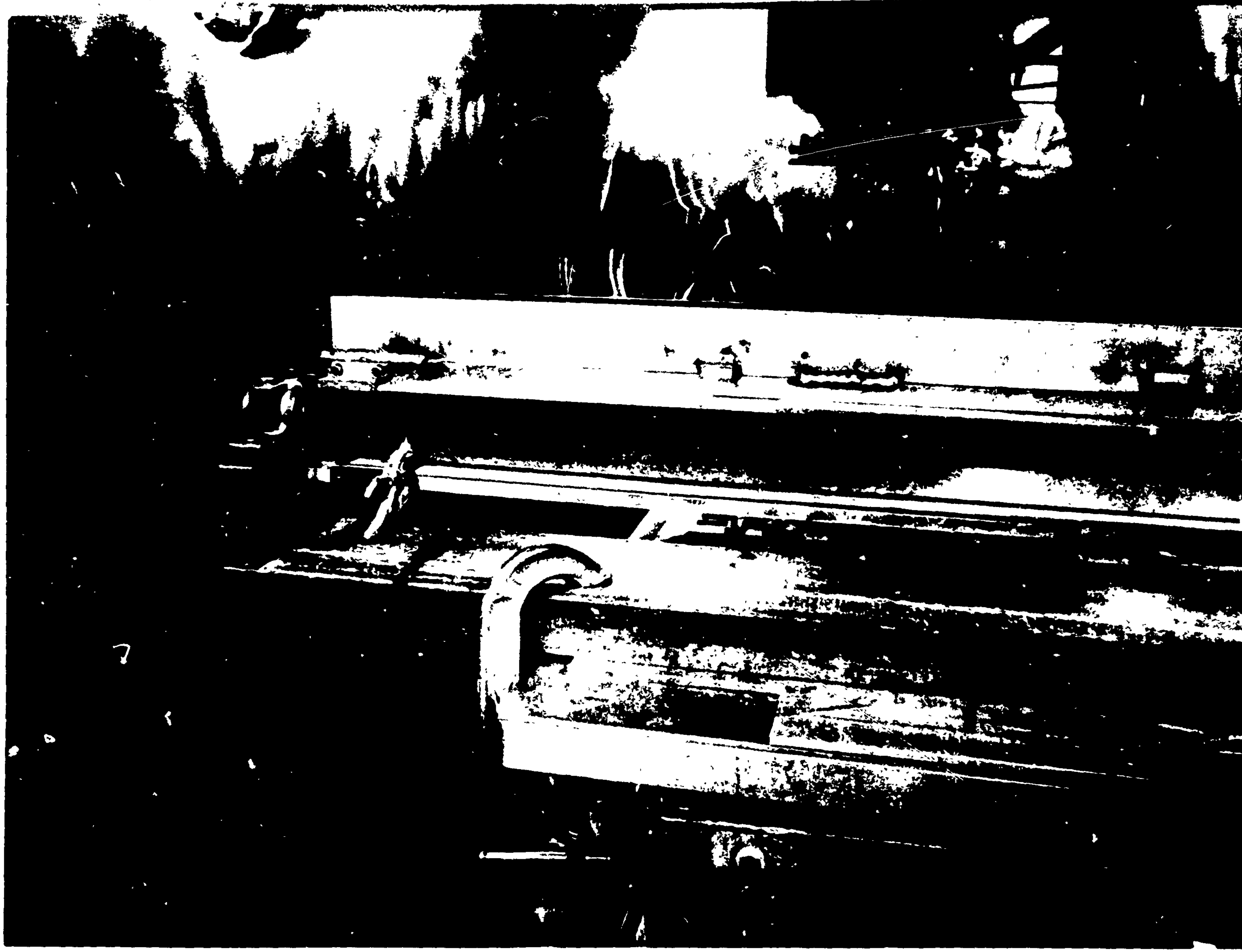


FIG. 2-40- ADDITIONAL TOOLING TO SECURE JOINT BEFORE ELECTRON BEAM WELDING

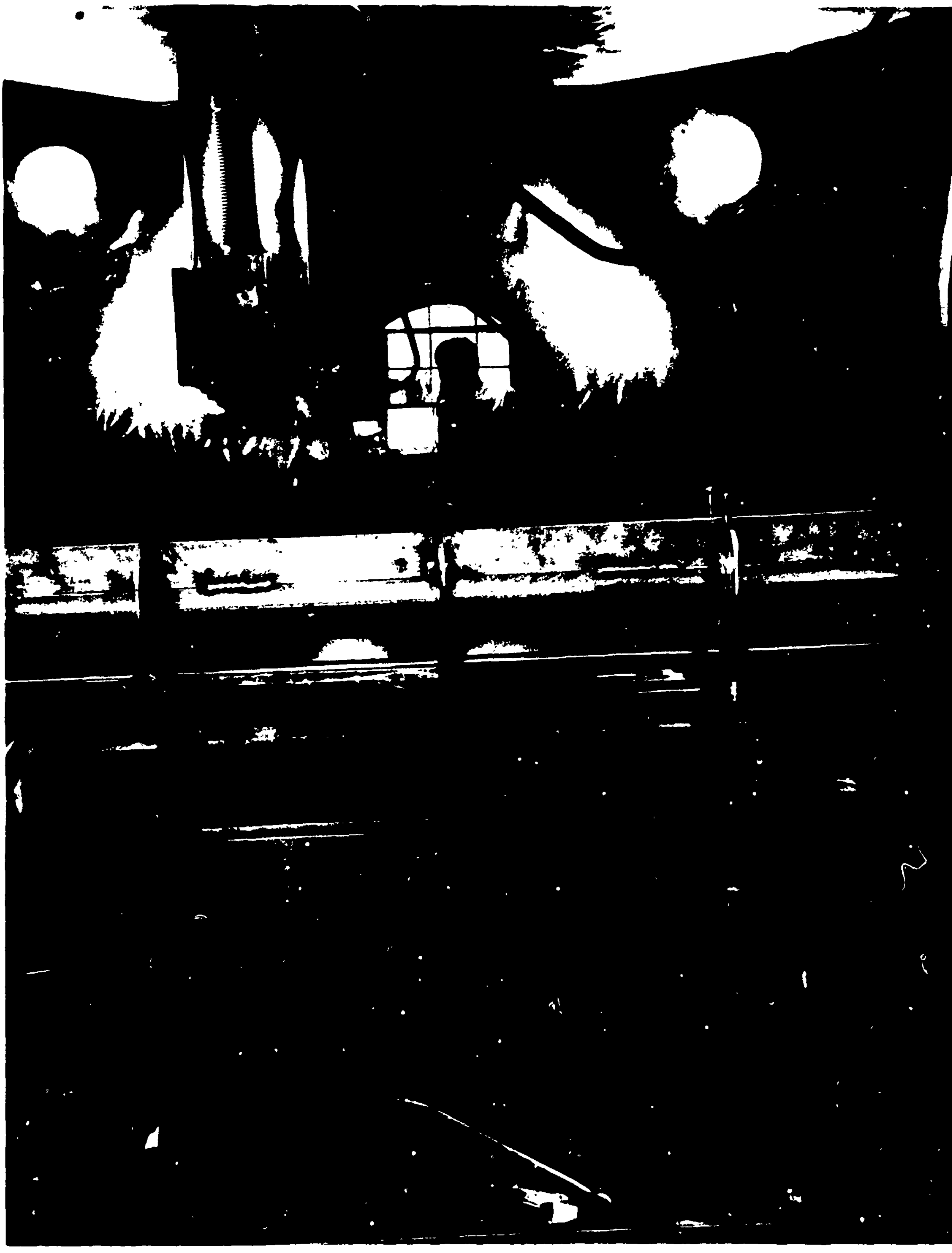


FIG. 2-41- FINAL TOOLING SETUP PRIOR TO WELDING OF THE 4-FT. LONG PANELS

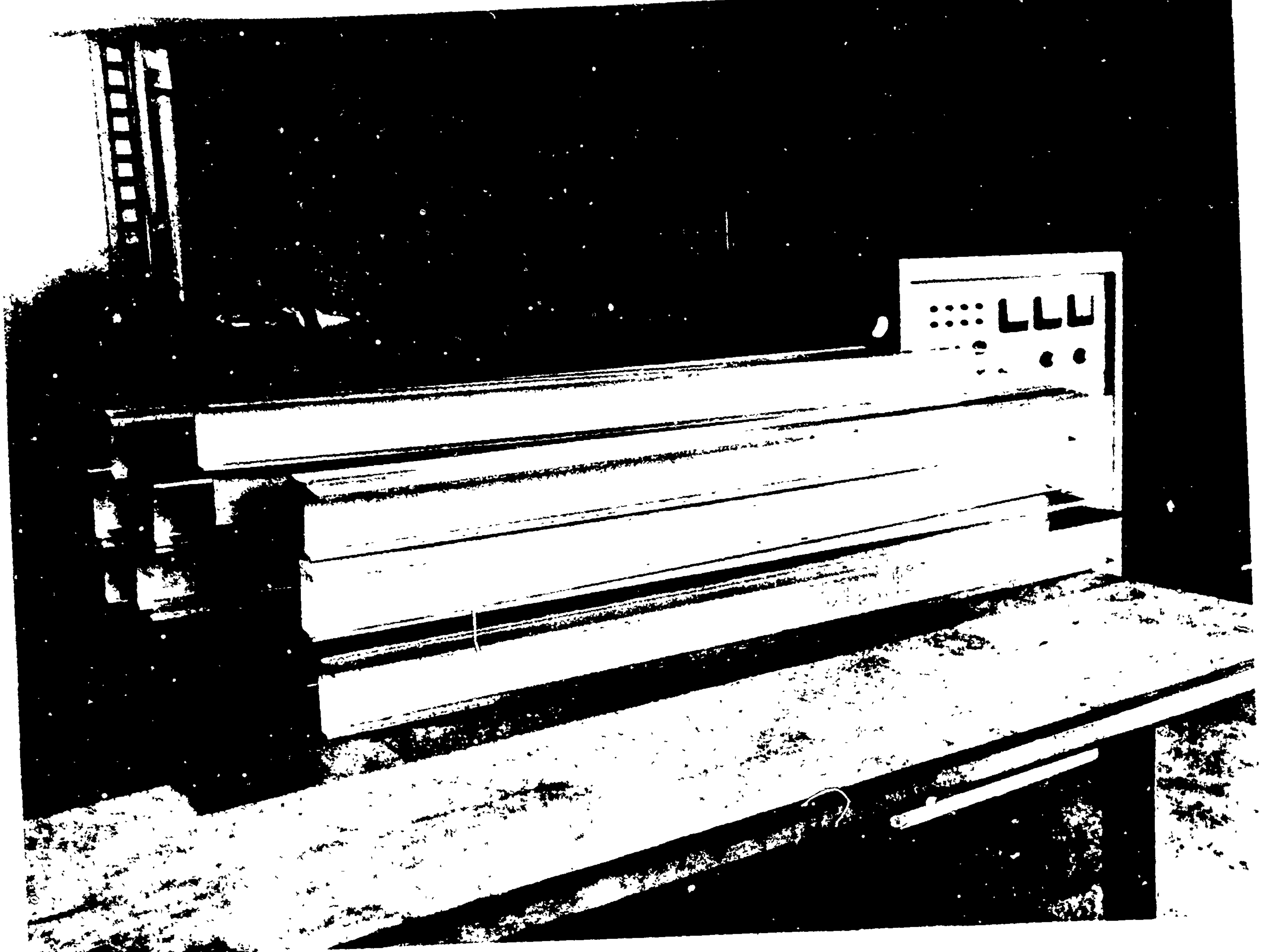


FIG. 2-42 FINAL "T" STIFFENED PANELS AS FABRICATED AT BABCOCK & WILCOX

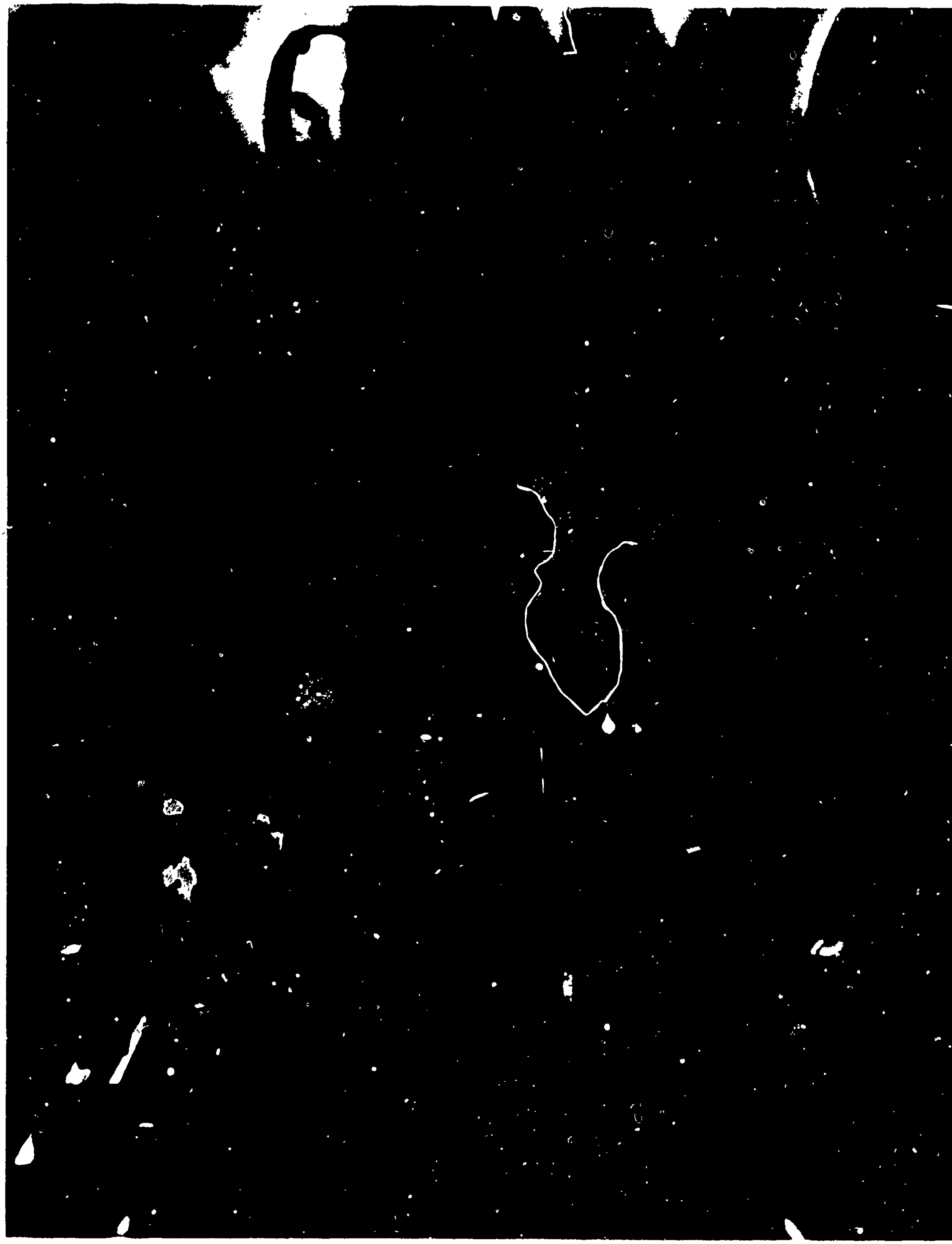


FIG. 2-43 - ELECTRON BEAM WELDTRUSION IN PROCESS ON "T" STIFFENED PANEL

2.2 Fabrication of Butt Weld Panels - Material used in this investigation was 3/16" 5456-H116 sheet. It was received in 240" x 96" sheets and saw cut or machined to the final dimensions so that the weld direction would be parallel to the sheet rolling direction. All sheet was degreased and wire brushed or etched prior to welding. The heat input for each of the joining processes is listed in Table 2-1.

2.2.1 Conventional GMA Welding (MIG) - Procedures were established to weld from one side and from both sides of the butt weld sample. A high travel speed was selected in an effort to minimize total heat input and thus minimize distortion. Several welding conditions, which were determined to be optimum in the conventional GMA fillet weld program, were also used in the butt weld program. These parameters were developed in both the conventional and pulsating fillet weld programs and are listed below.

1. Shielding gas mixture of 50% Ar - 50% He.
2. Starting and controlling equipment.
3. 3/64" diameter 5556 alloy electrode.

All panels were welded by the automatic GMA process without the aid of tacking.

High heat input, fast travel speed conditions were evaluated in two joint conditions. Single-pass square butt welds were made into a grooved, removable backing and compared to welds made by applying one weld pass from each side to determine a preferred procedure to minimize weld distortion.

2.2.1.1 Equipment and Fixture - The butt weld panels consisted of two 10" by 48" sheets joined to form 20" by 48" completed panels. These were welded in an 8-foot long Airline pneumatic fixture (see Figure 2-44). The Airline fixture is a long horn-type longitudinal weld seamer with pneumatic clamping onto the top of the stationary horn. The GMA welding head and controls were mounted on an attached side-beam carriage. All welding was done in the flat position with a minimal amount of air pressure on the weld samples.

The welding equipment included a Linde ST-21 water-cooled torch, Linde SEH-3 wire feed head, Linde type SCC-6 controller, Linde electronic governor - "Type E," and Linde OM-48 side-beam track and carriage unit.

The 1000-amp capacity Tek-Tran continuously variable slope D.C. rectifier power supply was used for the weld evaluation.

2.2.1.2 Welding Parameters - As specified before, all the 3/16" 5456-H116 sheet edges were saw cut and machined square and parallel prior to vapor degreasing. All joints were square butts without any gap between the sheets.

A total of four (4) 48" panels were welded by the conventional GMA process employing the constant energy (drooping V/A) power supply characteristic. A 50% argon + 50% helium gas shielding mix with a total flow of 60 cfh was used. Two of the panels were welded from one side with 100% weld penetration into an anodized aluminum backup bar possessing a .035" deep by .375" wide groove. The remaining two panels were welded with two passes, one from each side. The second pass was welded without back chipping.

The parameters for the one-side butt weld are listed below:

One-Side Weld

260 amps reverse polarity DC welding current.
25 volts arc voltage measured between the torch and work.
35 ipm travel speed.

Parameters for the two-sided weld are listed below:

Two-Sided Weld

Face Side	Root Side
260 amps	260 amps
25 volts	25 volts
70 ipm	67 ipm

All of the panels were pre-scribed for both shrinkage and out-of-plane distortion measurements prior to welding. The results of these measurements are given in paragraph 4.3. Typical cross sections of GMA weld are illustrated in Figures 4-24 (one side) and 4-25 (two sides).

Radiographic examination revealed all welds to be sound. Macrographic evaluation showed complete fusion of the welds.

2.2.2 Plasma-GMA Welds - Through arrangements by Rohr Corp., butt welds were made in 3/16" 5456-H116 sheet from one side only by the Plasma-MIG process developed by Philips Co., Netherlands. Sheets 10" wide by 20" long were saw cut, machined with square, parallel edges, and caustic etched at the Alcoa Technical Center. The material was packed in plastic-lined wooden crates with cardboard interleaves between the sheets of material and shipped to Philips. All welding parameters were developed by Philips.

Written instructions were sent to Philips about normal metal preparation, which included solvent wiping and wire brushing prior to welding.

2.2.2.1 Description of Process - The process can be described as GMA welding with a stream of plasma around the lower part of the filler wire. The plasma is generated in a stream of argon gas by an arc discharged between the workpiece and a nonconsumable electrode in the torch. A water-cooled copper nozzle is used to guide the plasma arc around the filler wire. In order to avoid pickup of air, shielding gas (Ar, Co_2 and He) is applied around the arc system. A general arrangement of the Plasma-GMA apparatus is shown in Figure 2-45.

Other arrangements can be used to provide the plasma around the electrode. An example of this is where the water-cooled copper nozzle of the torch acts as the plasma electrode. A photograph of the torch nozzle is shown in Figure 2-46.

Both of the electrodes (plasma and GMA) use reverse polarity D.C. power supply. The system is capable of using straight polarity D.C., but greater flexibility is attained with the reverse polarity (electrode positive). Employing reverse polarity DC with th plasma provides a "cleaning action" to remove the aluminum oxide ahead of the GMA-arc and is definitely preferable for aluminum welding.

2.2.2.2 Weld Fixture - The welding fixture used was a water-cooled fixture using a grooved, anodized aluminum backup bar. The 3/16" sheet was clamped in the fixture and butted tightly against its edge. A sketch of the weld fixture can be seen in Figure 2-48.

2.2.2.3 Basic Parameters - Twenty (20) sets of butt weld specimens were shipped back to the Alcoa Technical Center for evaluation. However, Philips welded all of the plates with various weld parameters. A list of the constant parameters is given below:

1. Plasma gas - 4.5 L/M argon + 1 L/M helium
2. Shielding gas - 17.5 L/M argon + 11 L/M helium
3. Nozzle diameter - 10 mm (.4")
4. Distance nozzle/workpiece - 14 mm (.55")
5. Wire extension in torch - 31 mm distance contact tube retracted beyond underside nozzle
6. Electrode - 1/16" diameter 5556 forwarded by Alcoa.

All of the plates were cleaned and clamped as mentioned before. A list of all of the weld parameters with the joint heat input is given in Table 2-6.

Upon receipt of the panels, all were radiographically inspected and found to be sound. Weld metal deposited was twice as wide as GMA process.

The panels were submitted for flatness measurements and mechanical property tests and are reported in Section 4.0.

2.2.3 Sliding Seal Electron Beam Welds - Through arrangements by Rohr Corporation, butt welds were made in 3/16" 5456-H116 sheet by Sciaky Brothers, Vitry, France, employing a mobile electron beam welding process incorporating a sliding seal in a "clamp-on" vacuum chamber. Sheets 10" wide by 100" long were saw cut parallel edges and caustic etched at the Alcoa Technical Center. The material was packed in plastic-lined wooden crates with cardboard interleaves between the sheets and shipped to Sciaky. All welding parameters were developed by Sciaky.

Instructions were given to Sciaky to solvent clean and wire brush the joint area prior to welding.

2.2.3.1 Equipment and Fixture - The equipment used was a Sciaky mobile electron beam welder with a 30 kilowatt output. The weld fixture and welding equipment are an integral system, since the electron gun and bellows cover the plate to be welded. (See Figures 2-48 and 2-49).

The features of the mobile electron beam used are as follows:

1. Output - 30 kilowatt output - 500 milliamperes - 60 kilovolts.
2. Travel Speed - .05 to 1 meter/min.
3. Vacuum System
   a. 1 roughing pump in gun housing
   b. 2 roughing pumps in plate housing
4. Optical Viewing System for Joint Alignment.
5. Sciaky Deflection System
   a. Variable frequency transverse oscillation
   b. Variable frequency longitudinal oscillation
   c. Circular sweep (pattern adjusted in diameter)
      (1) Circular sweep adjustment
      (2) Elliptical sweep adjustment
6. Automatic Pumping Sequency Control
7. Automatic Welding Sequence Control

2.2.3.2 Basic Weld Parameters - The welding parameter evaluation was divided into two categories: (1) Focus Selection, (2) Power Selection

The focus evaluation was initiated using the following weld settings: 55 kv, 46 ma, 2.54 kw, 100 cm/min. (40"/m) travel speed.

With this constant power input, four focus numbers were evaluated.

The above test results led to two focus numbers:

1. 860 - good bead shape.
2. 870 - good surface appearance.

Using these two focus numbers, an evaluation was made for the proper power selection for weld penetration. Sciaky felt there were two ways to go on penetration - partial and complete, both used aluminum backing bar. Consequently, they welded two 100" panels with full penetration and two 100" panels with partial penetration. Only the full penetration butt weld was evaluated upon receipt at Alcoa Technical Center.

The weld settings used to obtain the full penetration welds are as follows: 50 kv, 47 ma, 100 ma, 100 cm/min., Focus 870.

All welds were subjected to X-ray evaluation, out-of-plane distortion, metallographic and mechanical property evaluation. X-rays revealed sound weld metal. The test results of the sliding seal electron beam are reported in Section 4.0.

TABLE 2-6

SINGLE-PASS PLASMA-GMA BUTT WELDS IN 3/16" 5456-H116 ALUMINUM SHEET

Panel ID	Plasma Amp	Plasma Volt	GMAW Amp	GMAW Volt	Wire Speed (m/min)	Wire Speed (in./min)	Traverse Speed (cm/min)	Traverse Speed (in./min)	Width of Weld mm (in.) Upper Side	Width of Weld mm (in.) Under Side	Joules/in.
1	202	29.5	202	23.5	8.5	334.6	75	29.5	17(.67)	12(.47)	21,774
2	202	31.0	176	24.0	8.5	334.6	85	33.5	18(.71)	10(.39)	18,780
3	165	30.0	200	24.0	8.5	334.6	85	33.5	17(.67)	11(.43)	17,466
4	164	29.0	200	22.2	8.5	334.6	85	33.5	17(.67)	10(.39)	16,470
5	166	30.2	189	22.7	8.5	334.6	95	37.4	16(.63)	9(.35)	14,922
6	173	29.0	206	22.5	8.5	334.6	106	41.7	16(.63)	8(.31)	13,880
7	148	30.0	205	22.5	8.5	334.6	95	37.4	17(.67)	9(.35)	14,502
8	134	30.5	206	22.5	8.5	334.6	95	37.4	16(.63)	9(.35)	13,698
9*		32.0		23.0	8.5	334.6	95	37.4			
10	134	31.0	202	22.7	8.5	334.6	95	37.4	16(.63)	8(.31)	14,022
11	132	32.5	177	23.1	8.5	334.6	85	33.5	16(.63)	9(.35)	15,012
12	133	32.0	185	23.0	8.5	334.6	75	29.5	16(.63)	11(.43)	17,310
13	135	31.3	150	22.5	7.5	295.3	64	25.2	16(.63)	10(.39)	18,096
14	195	29.2	155	21.7	7.5	295.3	64	25.2	17(.67)	13(.51)	21,570
15	191	29.5	113	20.5	6.6	259.8	64	25.2	15(.59)	10(.39)	18,936
16	191	31.5	124	22.3	7.5	295.3	64	25.2	18(.71)	12(.47)	20,826
17	169	33.2	182	24.5	9.4	370.1	106	41.7	15(.59)	9(.35)	14,490
18	171	33.5	205	25.7	10.2	401.6	118	46.5	15(.59)	7(.28)	14,190
19	175	33.5	245	25.0	10.2	401.6	118	46.5	Spoiled		
20	171	29.0	165	22.0	7.5	295.3	64	25.2	17(.67)	12(.47)	20,448
21*	166	31	148	22.0	7.5	295.3	64	25.2	17(.67)	11(.43)	19,980

*Incomplete Data

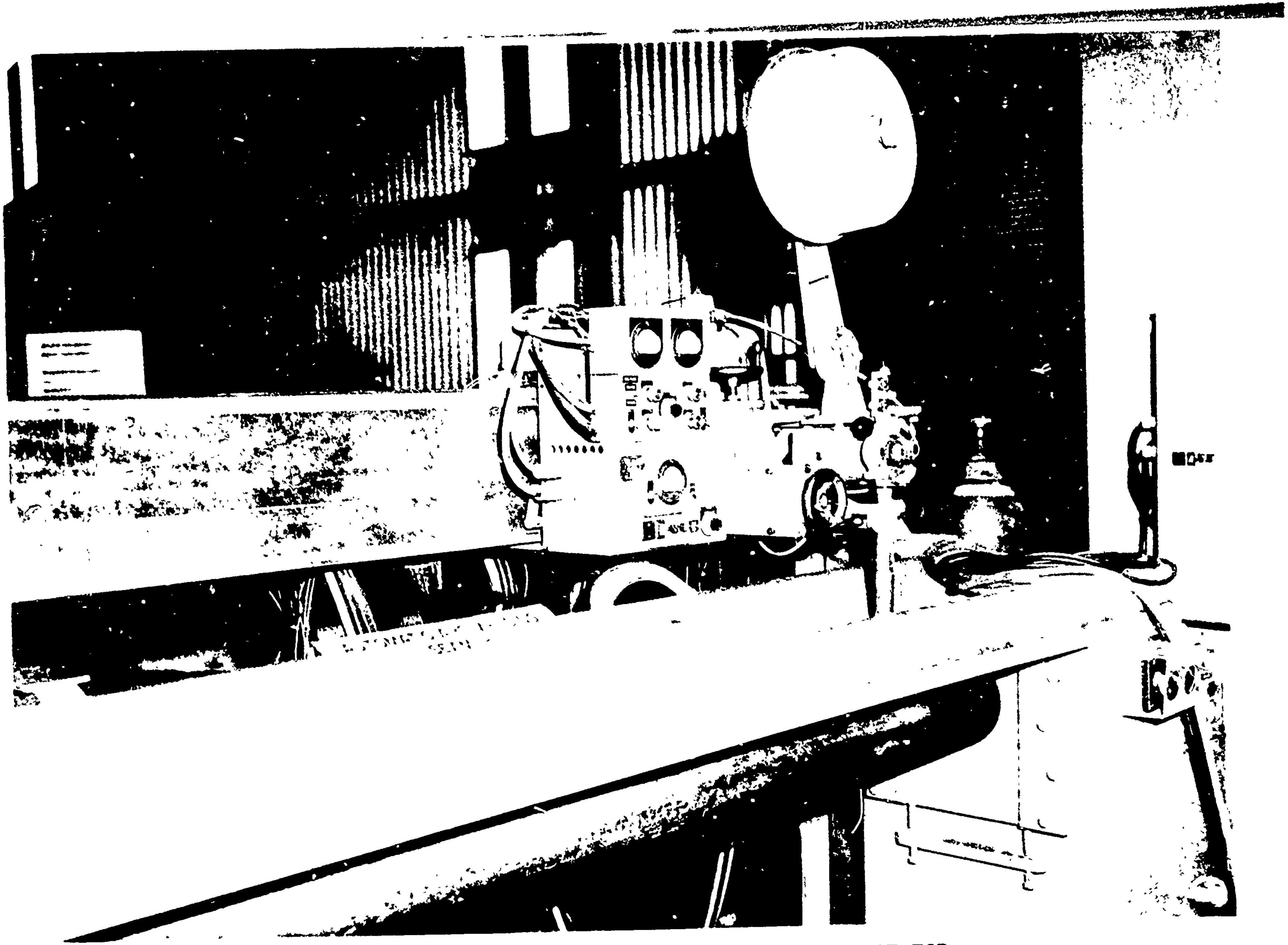


FIG. 2-44- 8-FT. LONG AIRLINE BUTT WELD FIXTURE FOR GMA WELDING

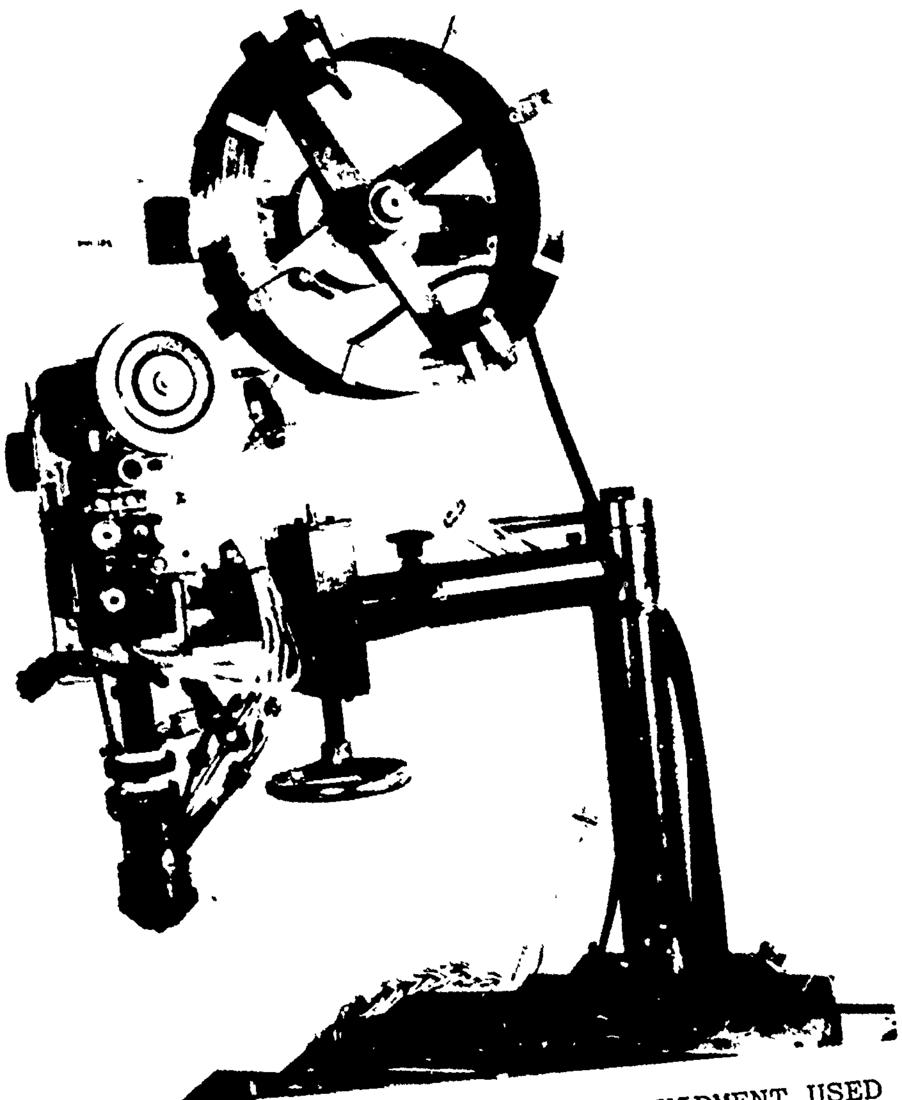


FIG. 2-45 PLASMA-GMA WELDING EQUIPMENT USED FOR BUTT WELDING

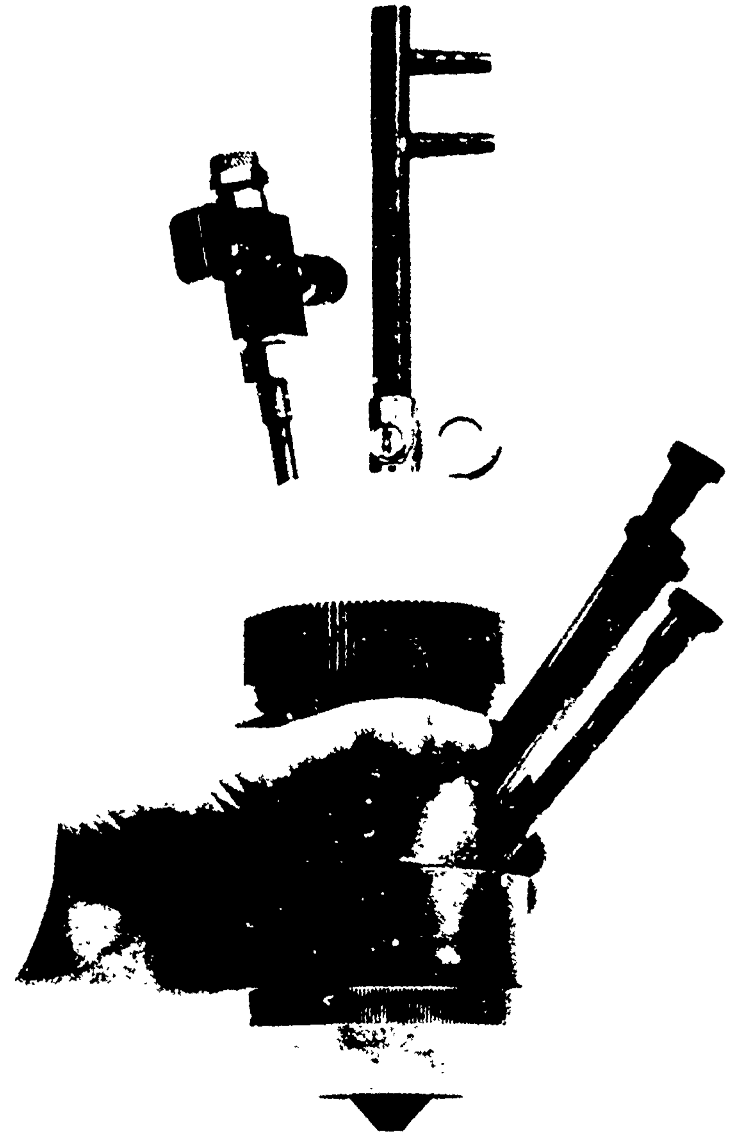


FIG. 2-46 PLASMA-GMA WELDING NOZZLE AS FABRICATED BY PHILLIPS CO.

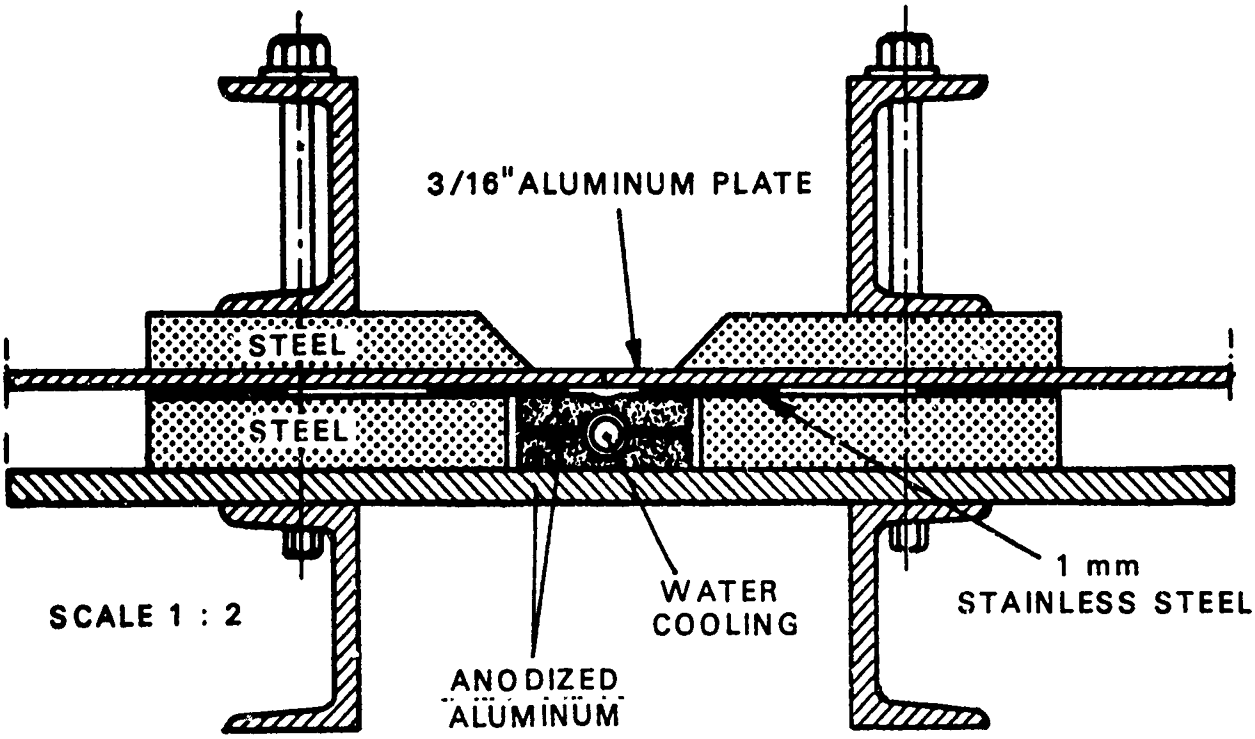
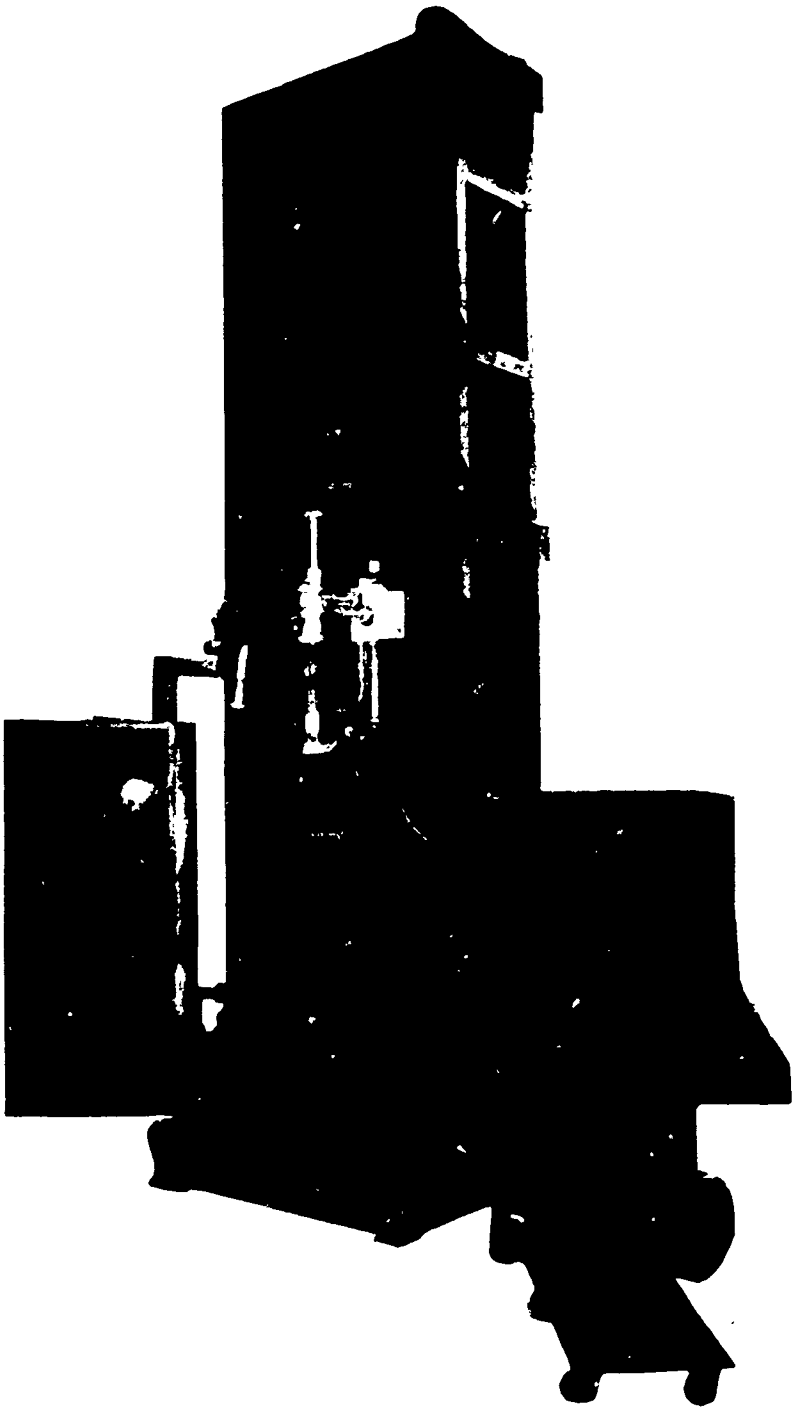
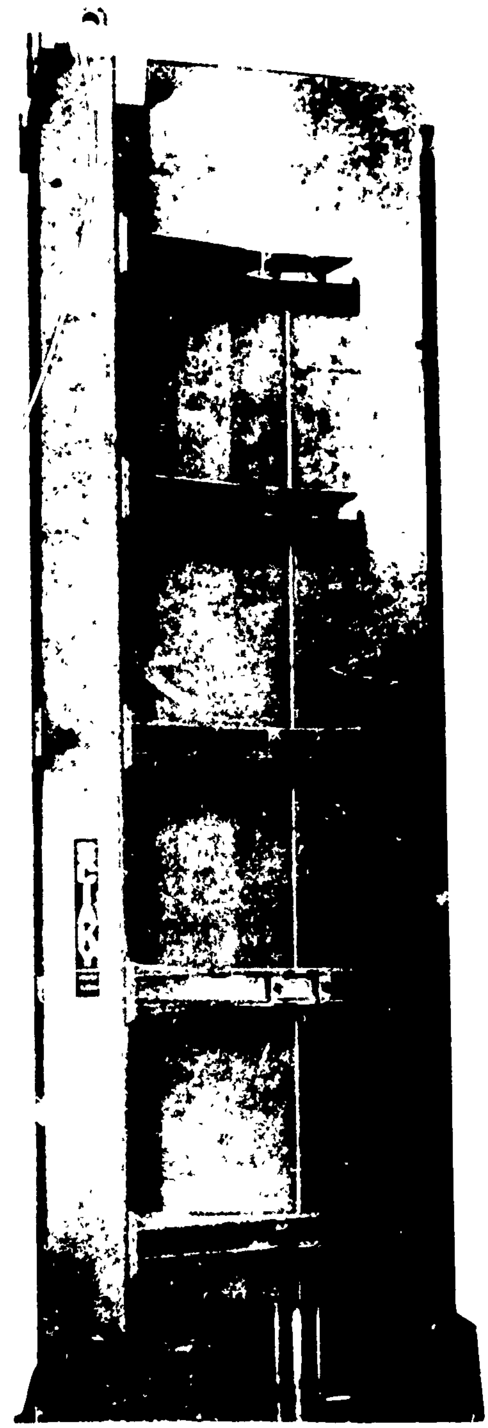


FIG. 2-47 WELDING FIXTURE USED FOR PLASMA GMA BUTT WELDS, FABRICATED BY PHILIPS, NETHERLANDS



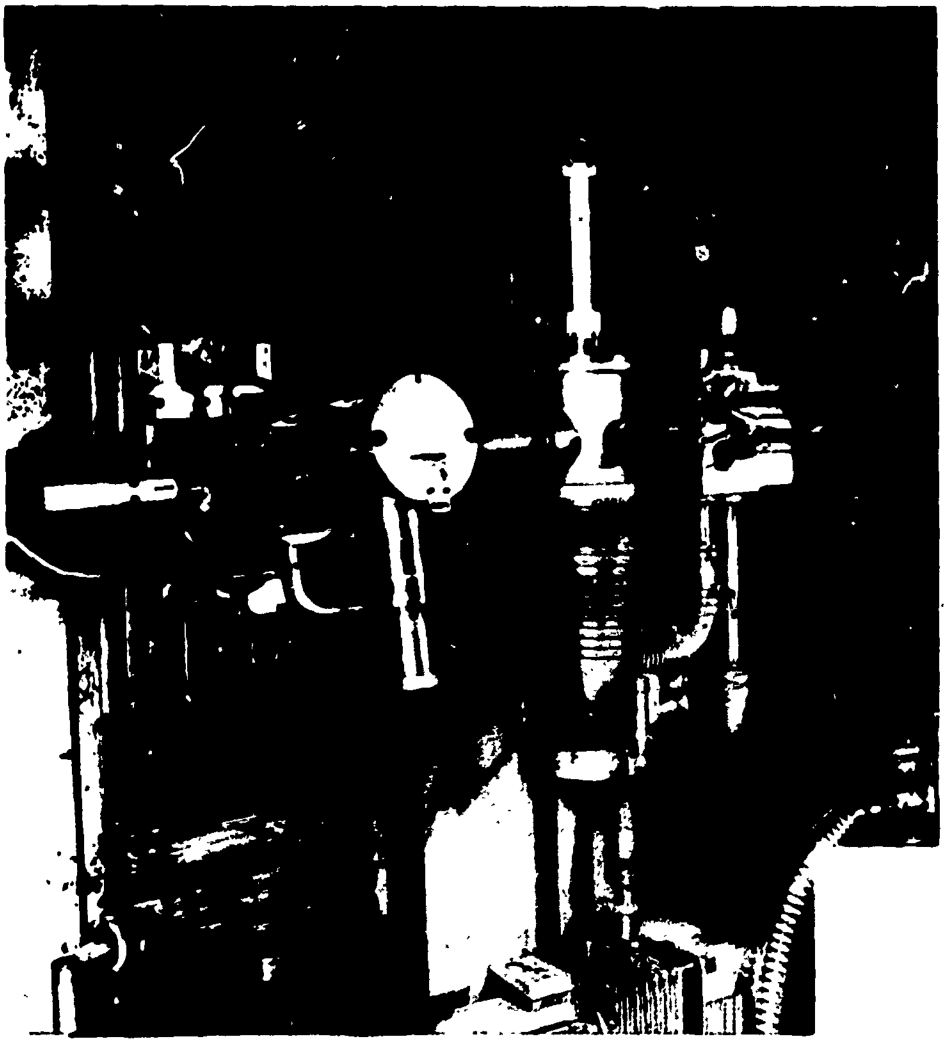


FRONT VIEW-ELECTRON BEAM GUN UNIT AND CONTROLS

REAR VIEW-PLATE TO BE WELDED IN POSITION

SCIAKY SLIDING-SEAL ELECTRON BEAM WELDER

FIG. 2–48



TRAVELING ELECTRON BEAM GUN UNIT AND BELLOWS COVERS WHICH MAINTAIN VACUUM ON PLATE BEING WELDED

SCIAKY SLIDING-SEAL ELECTRON BEAM WELDER

FIG. 2–49

Section 3 - Evaluation Procedure

3.1 General - Final "T" stiffened panels and butt-welded panels from the various weld processes were inspected for soundness, measured for distortion and subjected to static, fatigue and corrosion tests. A summary of the tests conducted is given in Table 3-1. The butt-welded panels for all three processes were subjected to a full evaluation. In the case of stiffened panels, panels from all 5 processes were submitted to a screening program including static and fatigue tests and distortion measurements. The best three processes, conventional GMAW, pulsed GMAW and HF resistance welding, were selected for additional fatigue testing and stress-corrosion tests. Photographs showing one of each type of stiffened panel evaluated are presented in Figs. 3-1 to 3-5. Plan view photographs of butt-welded panels as received for tests appear in Figs. 2-2, 3-6 and 3-7.

3.2 X-ray Inspection - All butt-welded panels were subjected to radiographic examination. The procedures used complied with MIL-STD-453 and showed a quality level of 2-2T. An OX-140 portable General Electric Industrial X-ray Unit of 140 KVP capacity was employed.

3.3 Ultrasonic Inspection - The fillet welded stiffened panels were inspected by means of ultrasonic techniques. The inspection was accomplished by the use of a twin contact transducer which could distinguish the amount of fusion in the fillet weld area. Details of the inspection techniques tried and the equipment chosen are given in Appendix A.

3.4 Distortion Measurements

3.4.1 Stiffened Panels - For conventional and pulsed GMAW panels made at the Alcoa Laboratories; 3 gage lines, 47-1/2 in. long were established on the sheet and the flange of the extrusion (both edges and center) for measuring longitudinal shrinkage of the panel. In addition, the change in width of the sheet at the ends and at mid-length also was determined. The shrinkage values were determined from readings taken before and after the welding was accomplished. Longitudinal shrinkage of panels fabricated at the Alcoa Laboratories was measured by means of a dial gage (0.001-in. divisions) and framework to span the 47-1/2 in. gage length. Transverse measurements were made by means of a micrometer which spanned the width of the sheet. For panels made by subcontractors, instructions were provided for scribe lines to be placed on the sheet of the stiffened panels. These scribe lines were to be measured before and after welding to the nearest 0.01 inch.

Out-of-plane distortions were made utilizing the apparatus shown in Fig. 3-8. The apparatus consists of a table with a thick steel plate top which has a surface precisely machined to be flat. Mounted on the table are machined slides and a corresponding traveling framework, also machined, to make accurate measurements in a 3 dimensional space. As shown, the stiffened panel was clamped securely at midspan and measurements were taken at predetermined locations along the length by means of dial gages. As many as 10 measurements were taken along the length of a 48-in. long panel. Three measurements, edges and center, across the width of the sheet and 3 measurements across the width of the extrusion flange also were made. These measurements established the longitudinal bow of the panel and the transverse out-of-plane distortion of the sheet. Measurements in the transverse direction to the edge of the sheet, top, center and bottom of the web of the extrusions and the edge of the extrusion flange were made to establish twist in the stiffened panel. As many as 160 measurements were made on some of the initial panels. Subsequently, the number of measurements was reduced because it was determined that the significant out-of-plane distortions could be defined with a smaller number of measurements.

3.4.2 Butt-Welded Panels - For the panels fabricated at the Alcoa Laboratories, shrinkage measurements were obtained longitudinally at the outside edges of the panel and four intermediate points. Transverse shrinkage values were determined at the two ends of the panels and at three intermediate points. To obtain transverse shrinkage values, the two plates to be joined by butt welds (10 in. wide x 50 in. long) were placed in intimate contact side by side and runout tabs were welded at each end to hold the plates together. Punch marks defining a longitudinal gage length of 49-1/4 in. were placed on the assembly and measurements taken. Likewise, gage lengths of 19-1/2 in. were placed on the panels for transverse shrinkage measurements. The measurements before and after welding utilized a dial gage (0.001 divisions) and an extension. For the panels made by electron beam welding instructions were provided to the subcontractor for scribe lines to be placed on the specimen and measured before and after welding for shrinkage measurements. Shrinkage measurements were not obtained for the panels made by Plasma GMAW because the panels were fabricated before instructions for shrinkage measurements were received.

Out-of-plane measurements for the butt-welded panels were made utilizing a similar setup to that employed for the stiffened panels (see Fig. 3-9). The butt-welded panels were supported on four points located approximately 1/4 of the length and width from the edges of the sheet. To avoid any distortions introduced in the panel by its dead weight, the bow was determined with the panel resting on its edge. The panel was then supported horizontally in the fixture used to make the measurments, and the supports were adjusted so that the panel had that same measured bow. Out-of-plane measurements were taken at six locations across the width, the two outer edges, on either side of the weld and at points midway between the edge and the welds, and at least 5 points longitudinally. Linear and rotary potentiometers were used to measure out-of-plane distortion. Data were logged by computer.

3.5 Residual Stress Measurements

3.5.1 Stiffened Panels - The sectioning method as illustrated in Fig. 3-10 was employed for determining residual welding stresses. In this procedure the panel was laid out in a number of longitudinal strips. Prior to cutting the section from the panel, gage marks were established and measurements taken on each strip. The part was cut into strips at lines shown and final readings were taken. The difference between the initial and final reading, multiplied by the modulus of elasticity, provided the amount of stress relief and thus the residual stress that existed in the part. Most of the residual stress determinations were made with a Berry strain gage (mechanical) which has a 2-in. gage length. Several electrical resistance strain gages were applied to the initial specimen to assure that an accurate representation of residual stresses was determined for the section by the use of mechanical gage measurements only. The electrical resistance gages were employed because the mechanical gages could not be used on both surfaces of all parts of the section because of the clearance available. Fig. 3-11 shows a stiffened panel which has been laid out with punch marks. Three electrical resistance strain gages can be seen on the sheet. Subsequently, individual longitudinal strips containing the punch marks were isolated from the specimen to obtain the residual stress pattern.

3.5.2 Butt-Welded Panels - The method of sectioning also was employed for these panels. In this case, measurements could be made on both surfaces of the plate so that mechanical gage measurements employing the Berry strain gage were employed only. The plate was laid out with 17 strips oriented parallel to the direction of the weld. Readings taken before and after the strips were cut from the panels were utilized to determine the residual stress pattern in the panels. One residual determination was made from each type of panel.

3.6 Hardness Measurements - A full section piece of the stiffened panel or butt welded panel approximately 1/4 in. long was cut from three specimens of each process. One surface of the cross section was polished suitable for hardness determinations. Rockwell "B" values were determined for the section. Readings were taken primarily in the region of [illegible]d to determine the extent of heat-affected material.

3.7 Exfoliation and Stress Corrosion Test Procedures - Exfoliation and stress corrosion tests were conducted on 5456 alloy weldments to determine if the various welding processes under study had an effect upon the resistance to exfoliation and stress-corrosion cracking (SCC). Included were specimens heated one week at 212 F to produce metallurgical changes simulating natural aging that may occur during many years of service. In all tests the weld beads were left intact. Stress corrosion tests of fillet weldments involved the following weld processes:

(1) Pulsed GMAW
(2) Conventional GMAW
(3) High Frequency Resistance Welding

In the case of butt welds the following weld processes were tested.

(1) Conventional GMAW
(2) Plasma GMAW
(3) Sliding Seal - Electron Beam Welding

3.7.1 Accelerated Exfoliation Test - Duplicate specimens of the parent 3/16" thick 5456-H116 sheet, fillet weldments (approximately 3 inches of weld) and butt weldments (about 1.5 inches of weld) were exposed to the ASSET exfoliation test. This test is recommended by the Aluminum Association Task Group on Exfoliation and Stress Corrosion Testing as a substitute for the corrosion test presently required in the Interim Federal Specification QQ-A-00250/19 and 20.

3.7.2 Stress Corrosion Tests - Beam specimens 36 inches in length as shown in Figure 3-12 were prepared from fillet weldments and stressed to 75% of the minimum guaranteed yield strength of the 5456-H116 sheet. In order to stress the sheet to 75% of the yield strength of the parent metal and additional plate approximately 1/2" x 3" of 6061-T6 alloy was bolted to the flange of the extrusion to prevent buckling of the stiffener. The interface of the 6061-T6 plate was painted to minimize the possibility of increasing the applied stress as a result of crevice corrosion. Duplicate assemblies of each process were exposed to the 3-1/2% sodium chloride alternate immersion test per Method 823 of Federal Standard 15 1b in both the as-welded and heated conditions (Figure 3-13).

Tensile properties for butt welds based upon a 10 inch gage length indicated that the weldment yield strengths were similar to the yield strength of the parent sheet. Consequently, duplicate beam assemblies in the as-welded and heated (1 week at 212 F) conditions were stressed to 75% of the guaranteed minimum yield strength of the 5456-H116 sheet and exposed to the 3-1/2% NaCl solution by alternate immersion.

3.8 Static and Fatigue Tests

3.8.1 Stiffened Panels - With the exception of the explosion joined panels two static tests were made of panels from each process. One panel only was available for the explosion joined process. Fig. 3-14 shows the setup used for these tests. Heavy end fixtures were employed at the supports. The panels were tested using a span of 36 in. and two load points spaced 7 in. apart. A 1/2-in. thick x 3 in. wide plate of 6061-T6 was bolted to the flange of the stiffener to prohibit local and lateral buckling of the specimen. Plate stiffeners, 1/2-in. thick, were placed on each side of the web under each load point to prohibit crippling of the web. The span and stiffening elements were utilized so that tensile stresses on the order of the tensile strength of the sheet material could be developed at the welded joint and so that high shear stresses could be developed in the joint between stiffener and sheet. The specimen was loaded either to failure or to the maximum deflection available in the setup. The apparatus employed in the measurements is shown in Fig. 3-15. Load, strain at midspan, midspan deflection and change in span were logged by computer for subsequent analysis.

Flexural fatigue tests were made in a 50 kip Templin structural fatigue machine utilizing the test setup shown in Fig. 3-16. Tests were performed at a stress ratio, R, of 0.05 at a rate of about 5Hz. Panels had a 32-in. span with two load points centered in the span and spaced 8-in. apart. The specimen was oriented so that the flange with the joint (sheet side) was subjected to tensile loading in the tests. Tests were made in air and sea water. In the tests with sea water a trough was attached to the specimen in the high stress, central portion of the beam and was sealed to hold the sea water. A substitute ocean water, without heavy metals, prepared according to ASTM Specification P1141-52, was utilized in the tests.

<u>3.8.2 Butt Welded Panels</u> - Two specimens of the type shown in Fig. 3-17 from each of the three processes considered were subjected to full section tensile tests. A yield strength based upon a 10-in. gage length and a total elongation in 10-in. were determined in addition to tensile strength. Axial stress fatigue tests employing the specimen shown in Fig. 3-18 were made in air and in sea water. A zero stress ratio was used for these tests. The tests were performed in a 15 kip Krouse Fatigue Machine at a rate of 13.3 Hz. For the tests in sea water the reduced section of the specimen was contained in a plastic bottle bonded to the grip end filled with sea water. The setup is shown in Fig. 3-19.

<u>3.9 Metallographic and Fractographic Examinations</u> - One half in. long sections of the complete cross section of stiffened panels and butt welded panels were removed for metallographic studies. Three samples were taken from each welding process. One surface of the specimen was subjected to a metallographic polish and electro polished to reveal the grain structure of the weld. Photomacrographs were taken at approximately 15X magnification. Microscopic examinations were also made to evaluate weld quality.

Figure 3-1 - Pulsed GMAW Specimen

Figure 3-2 - Conventional GMAW Specimen

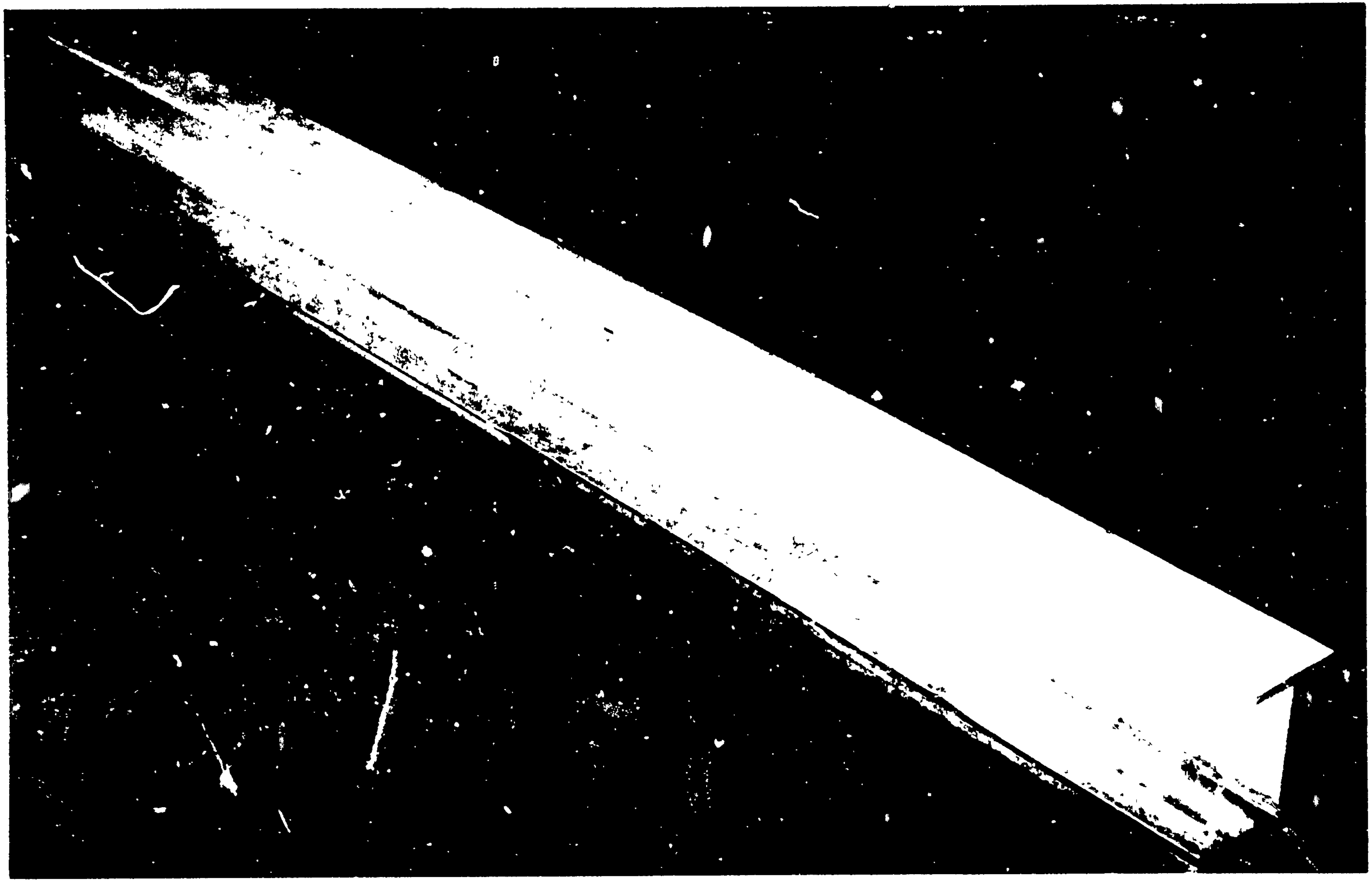


Figure 3-3 - Explosion Welded Specimen

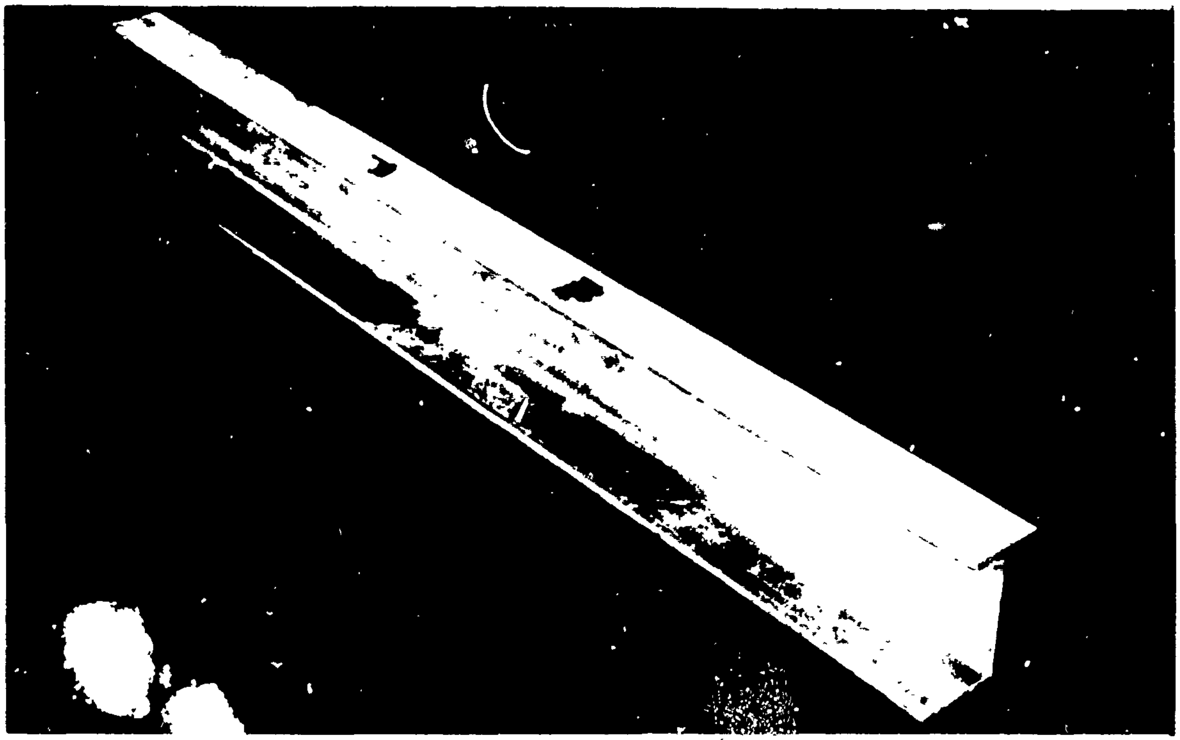


Figure 3-4 - In Chamber Electron Beam Specimen

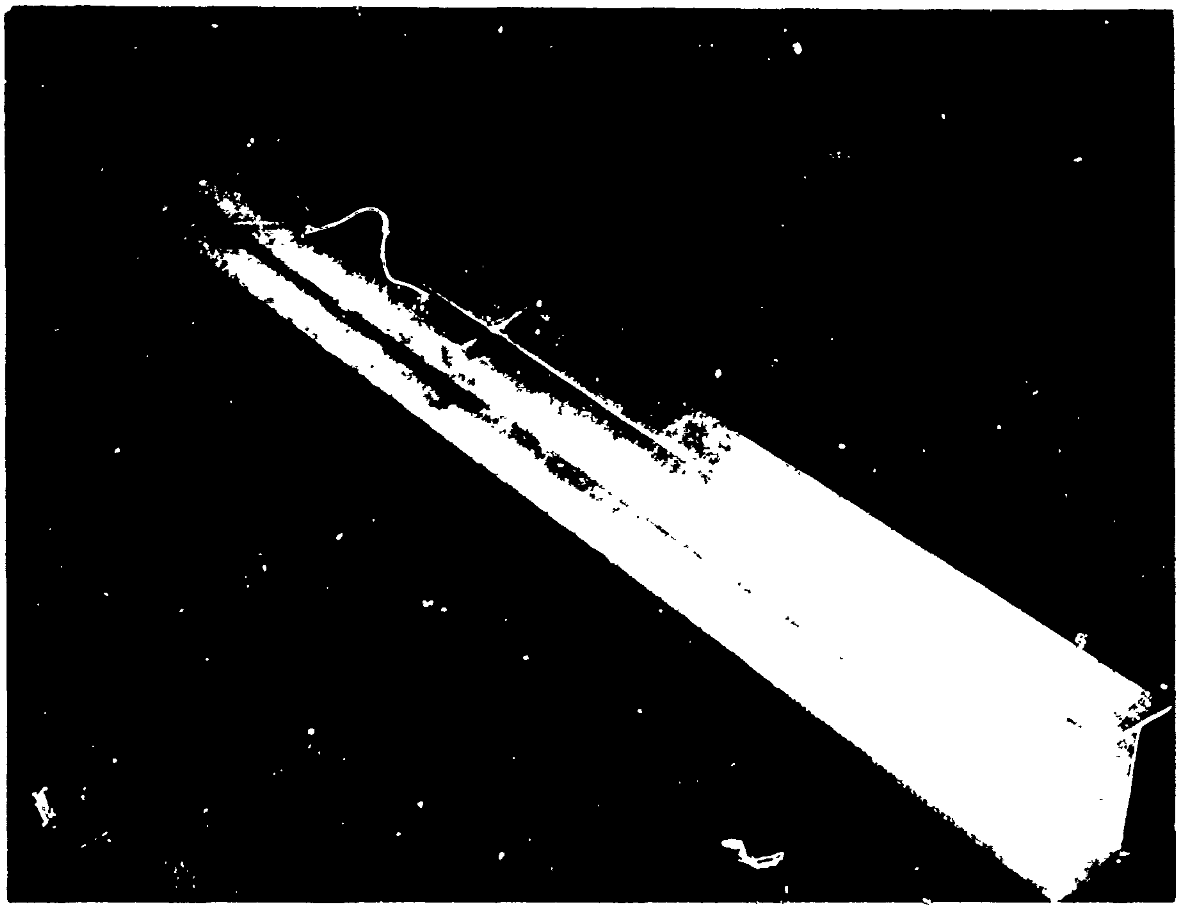


Figure 3-5 - HF Resistance Welded Specimen

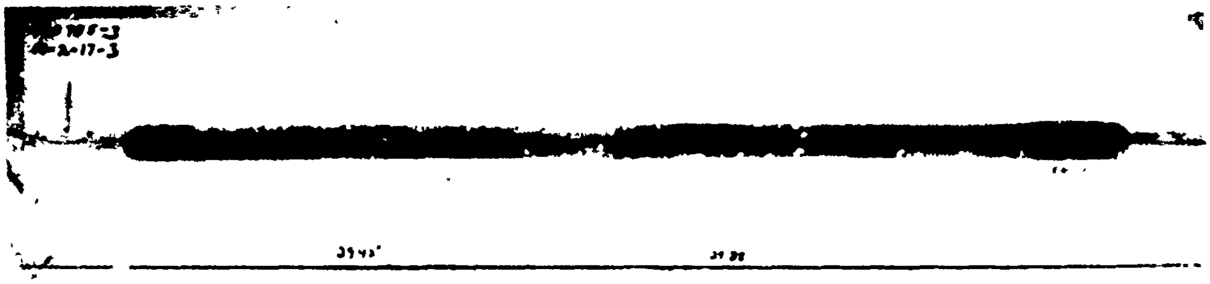


Figure 3-6 - Sliding Seal-Electron Beam Welding
(20" x 100" panel)

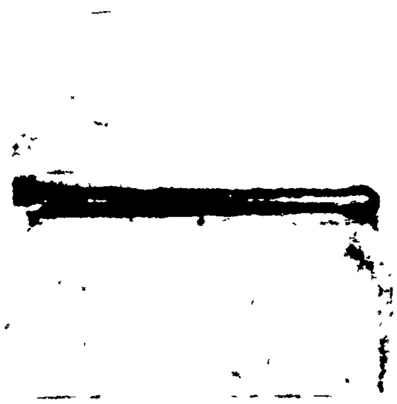


Figure 3-7 - Plasma GMAW (20" x 20" panels)

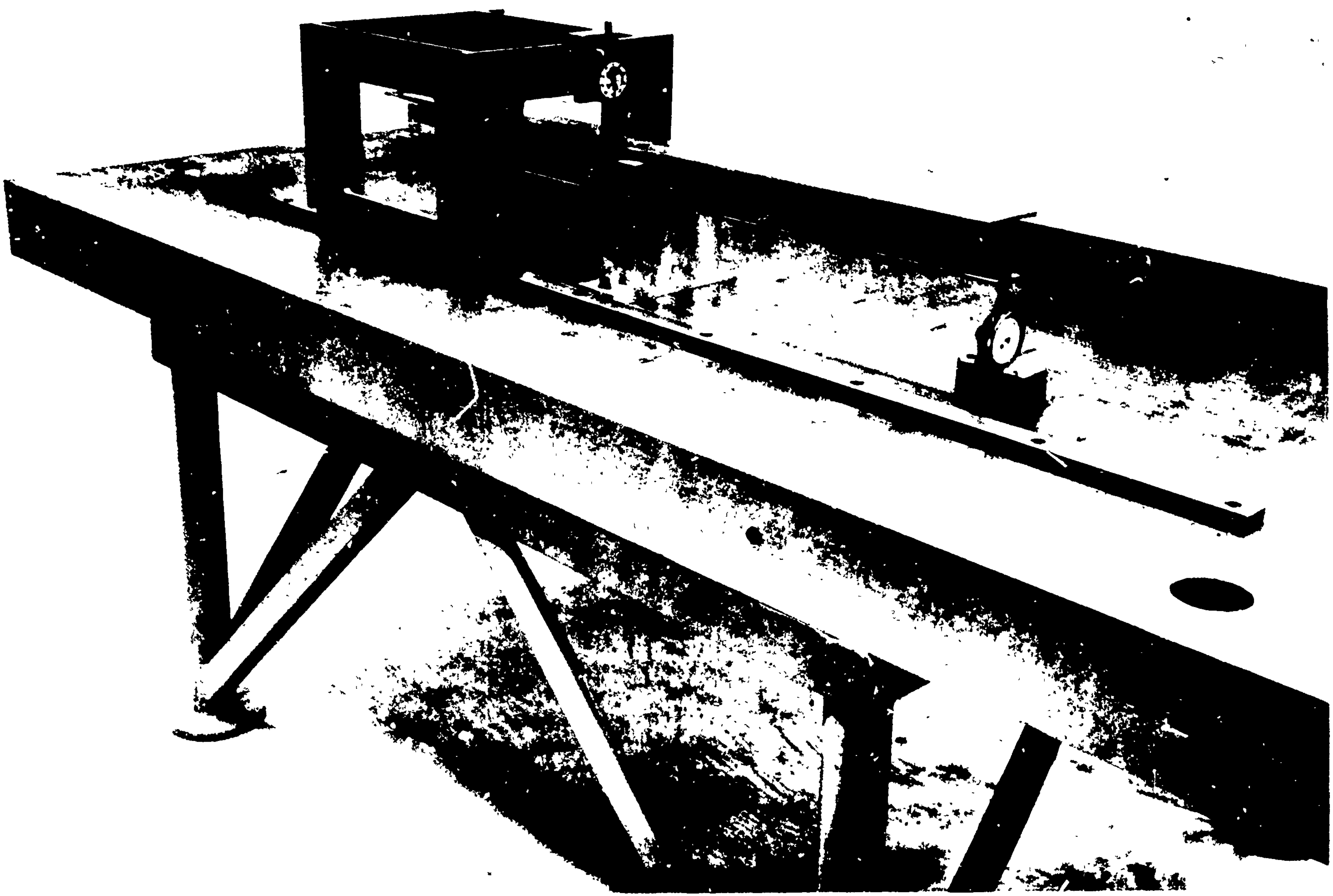


Figure 3-8 - Apparatus for Out-of-Plane Measurements

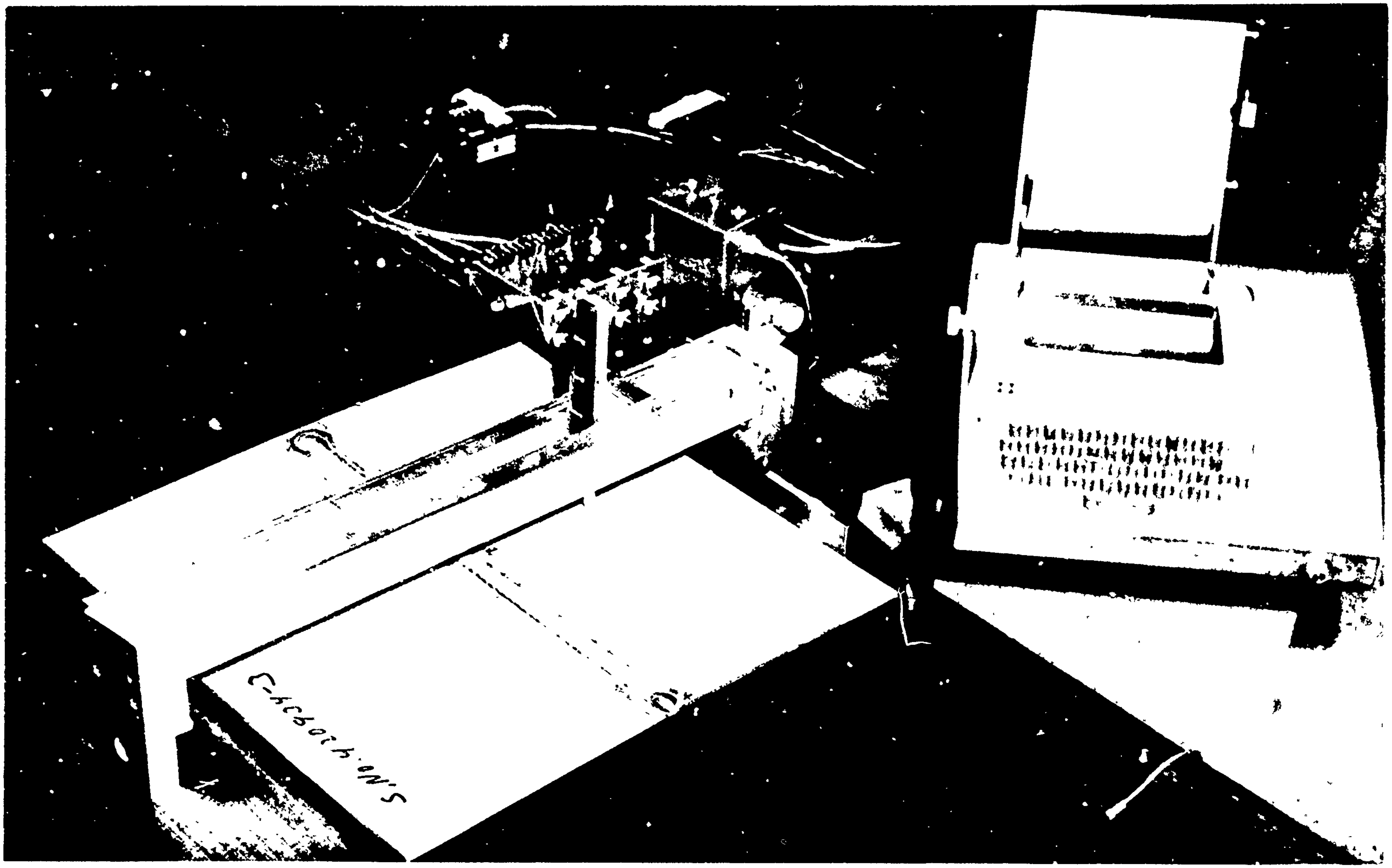
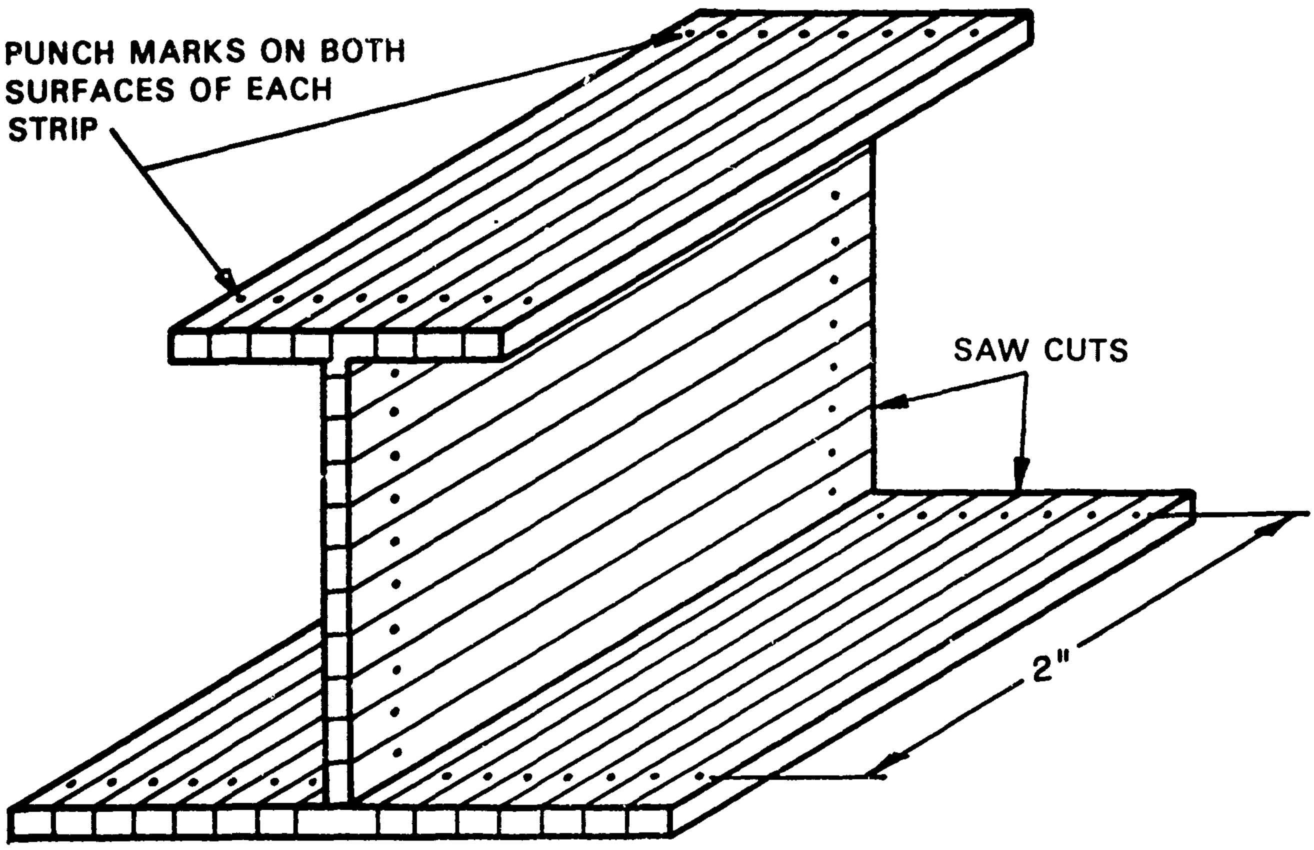


Figure 3-9 - Apparatus for Out-of-Plane Measurements
of Butt-Welded Panels



SECTIONING METHOD FOR MEASURING
RESIDUAL WELDING STRESSES

FIG. 3-10

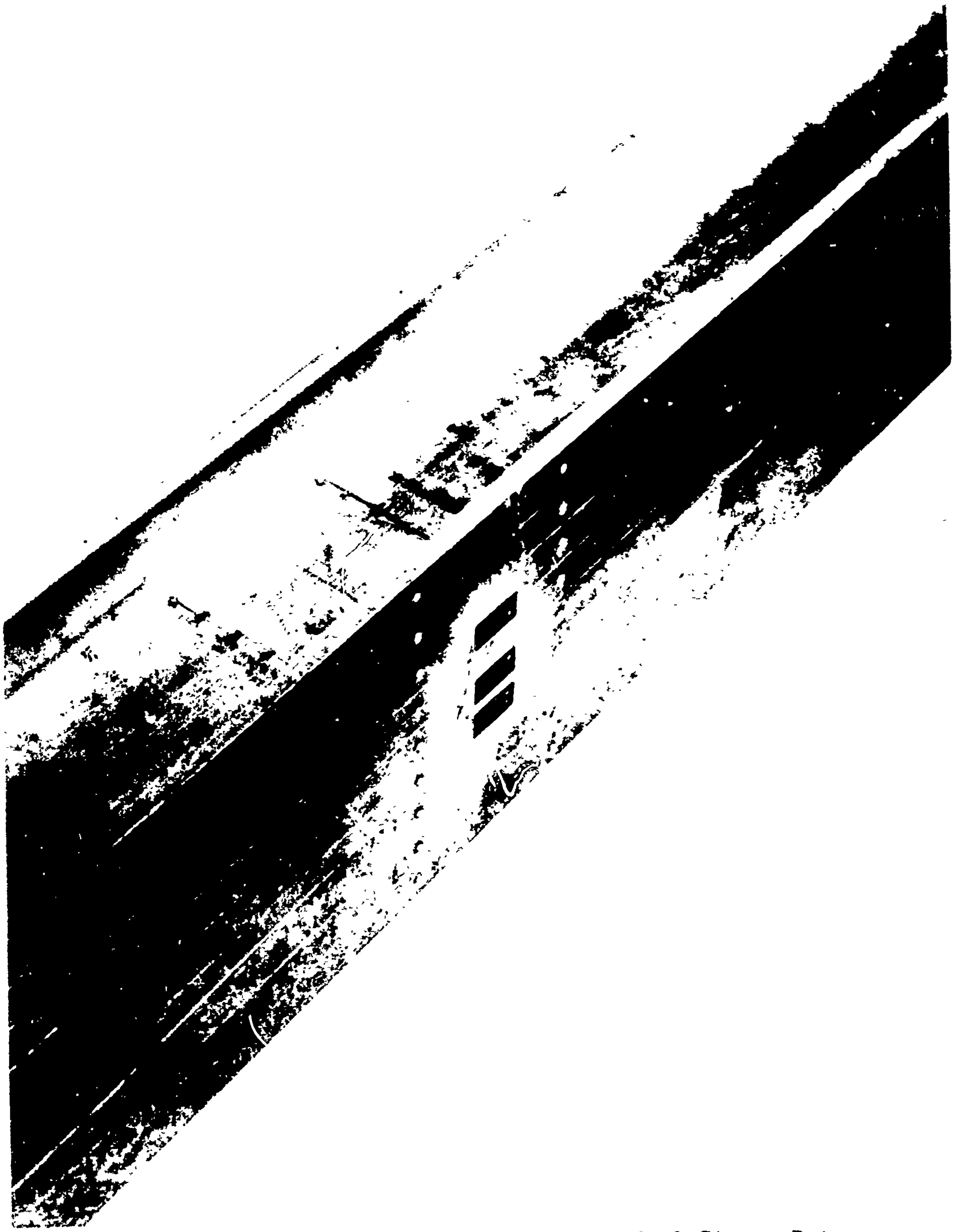


Figure 3-11 - Grid Layout for Residual Stress Determination

0012507

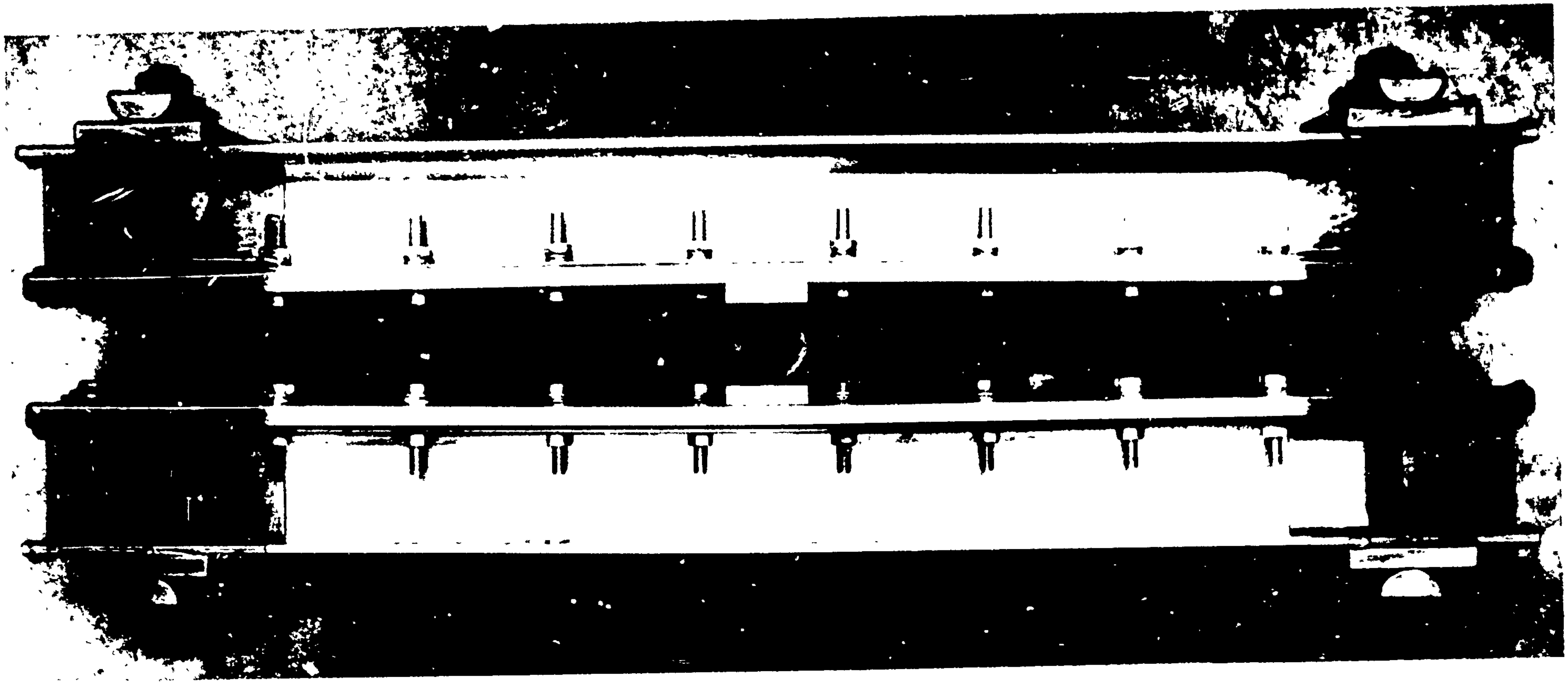


Figure 3-12 - Beam Stress Corrosion Assembly For
Fillet Weldments

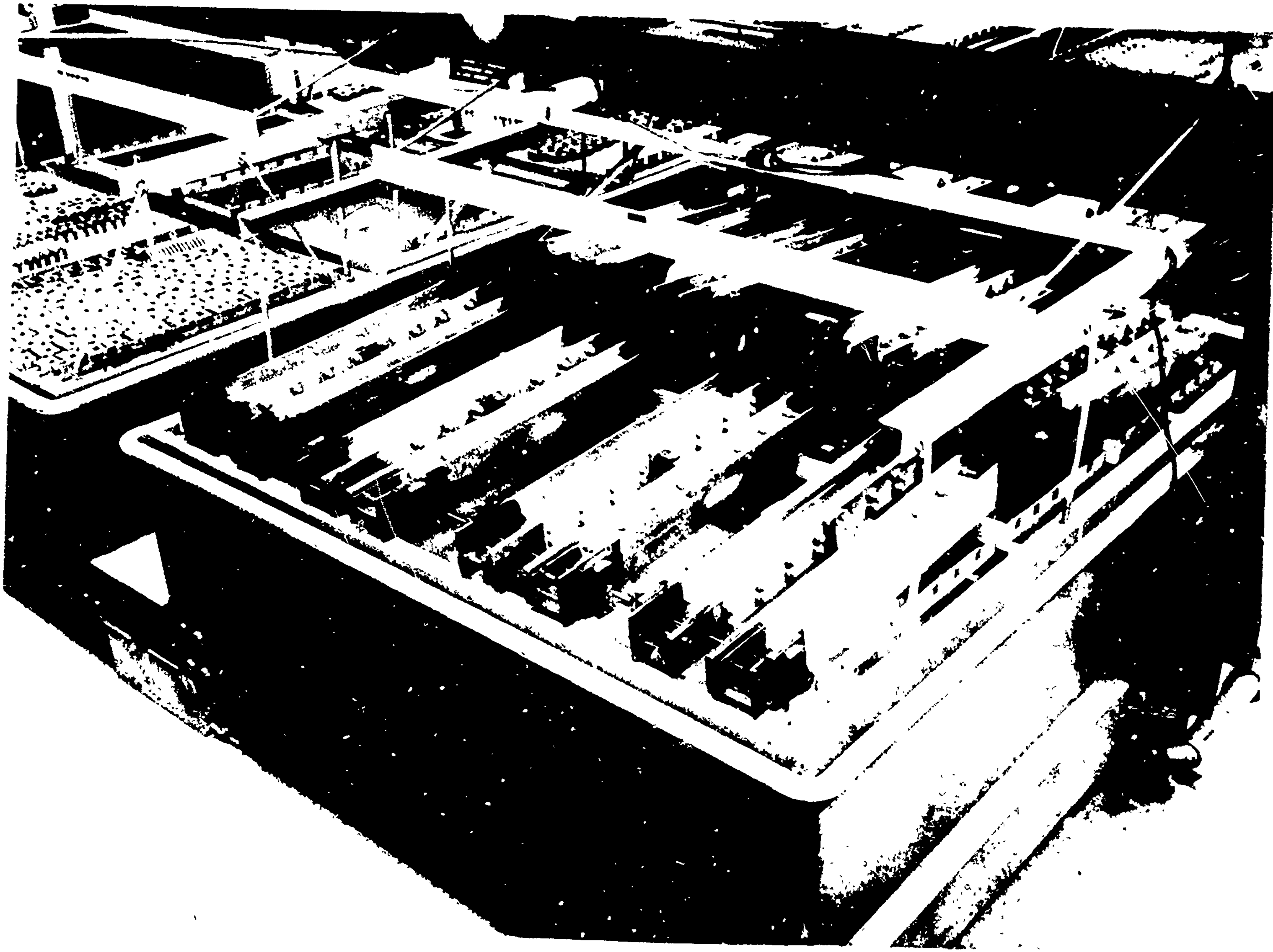


Figure 3-13 - Beam Stress Corrosion Assemblies Exposed
to 3-1/2% NaCl Alternate Immersion Test

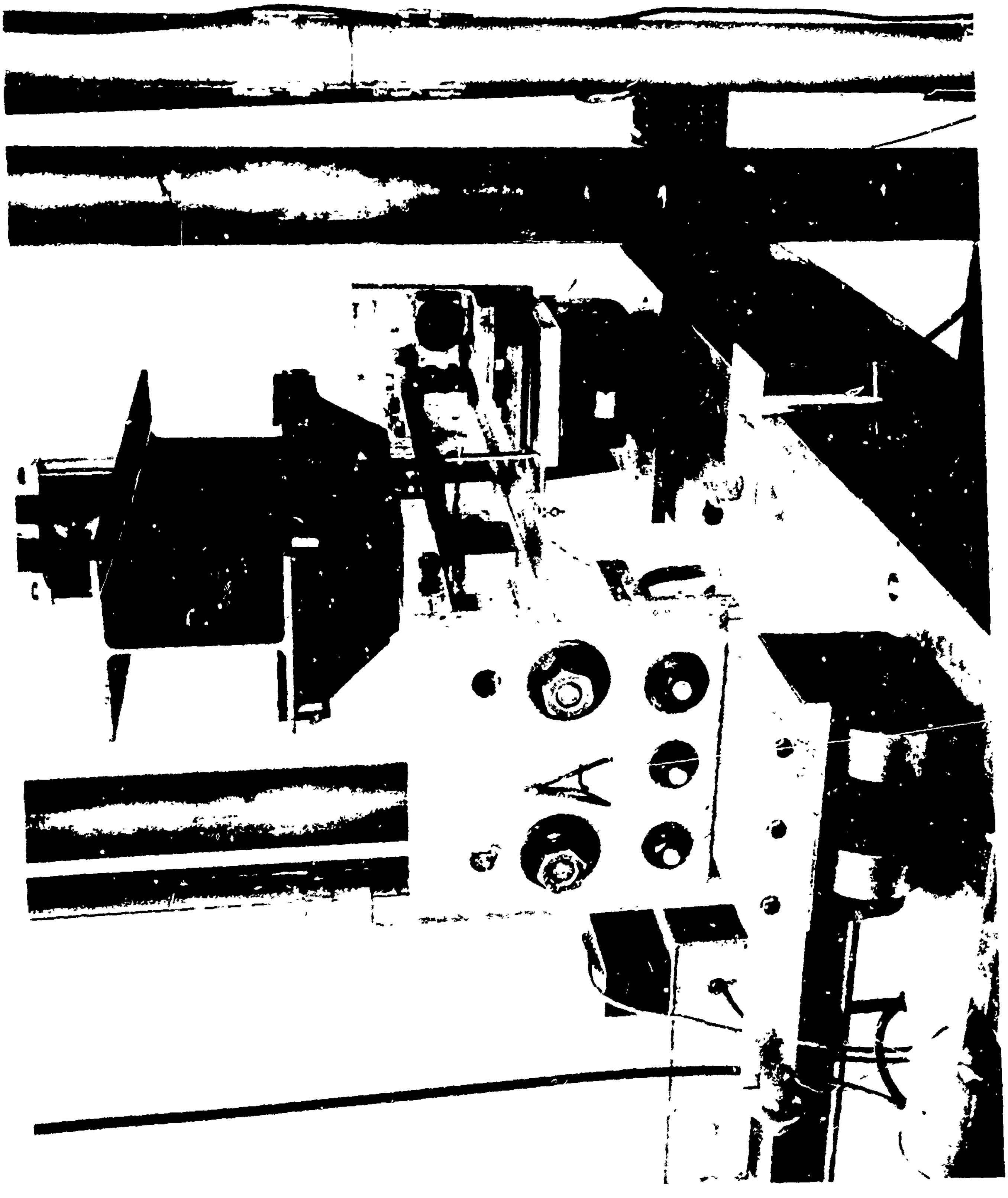


Figure 3-14 - Test of Stiffened Panel

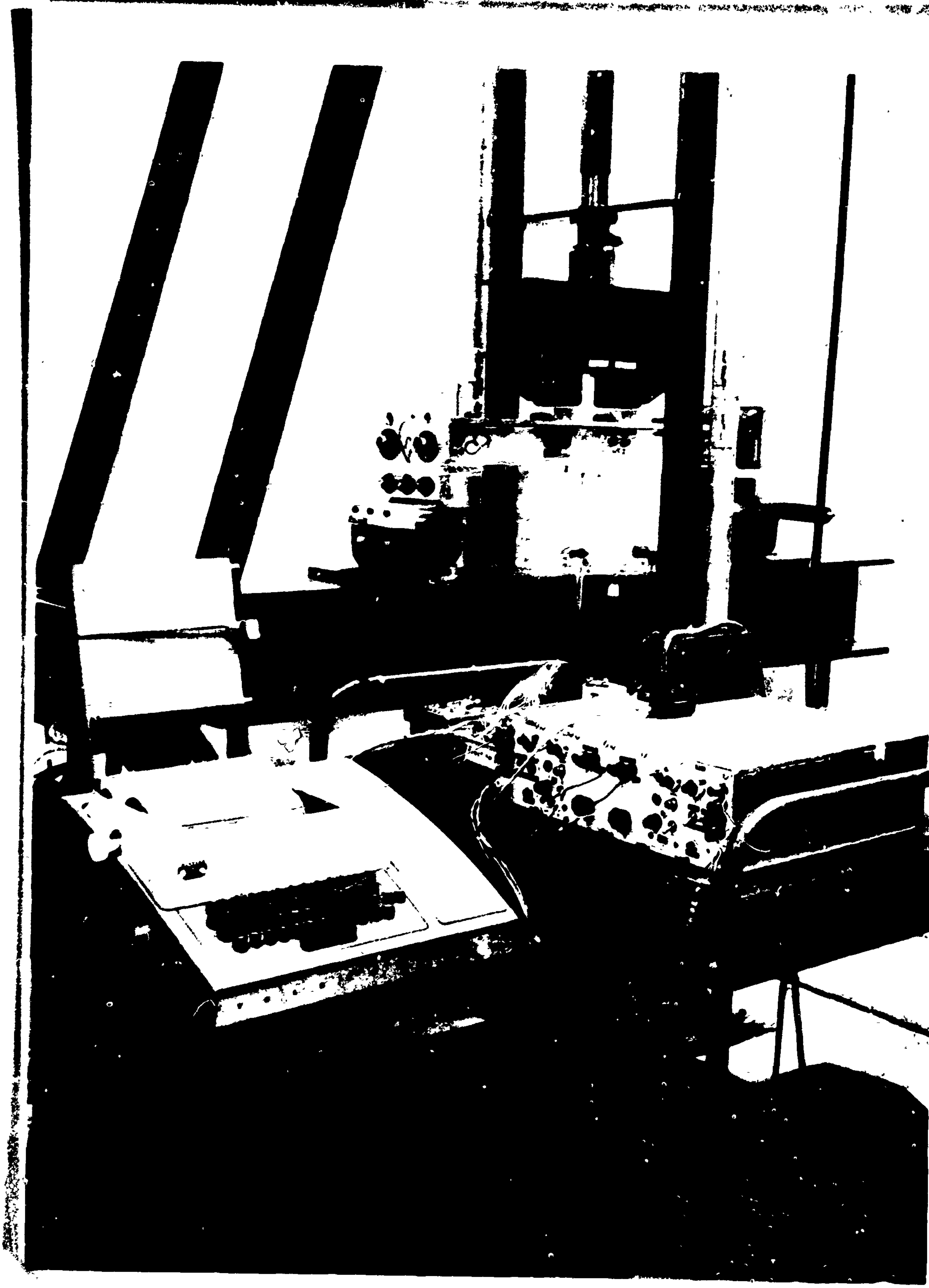
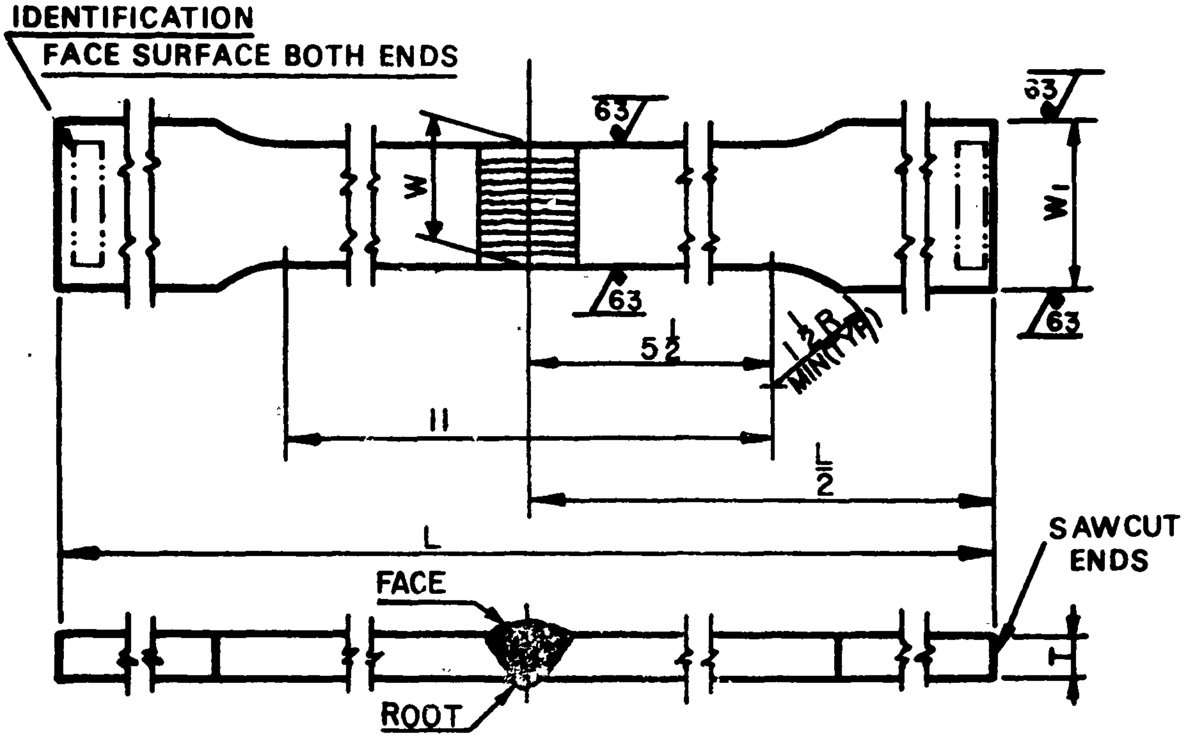


Figure 3-15 - Apparatus for Bending Tests of Stiffened Panels



TENSILE SPECIMEN — ☐ REQD.

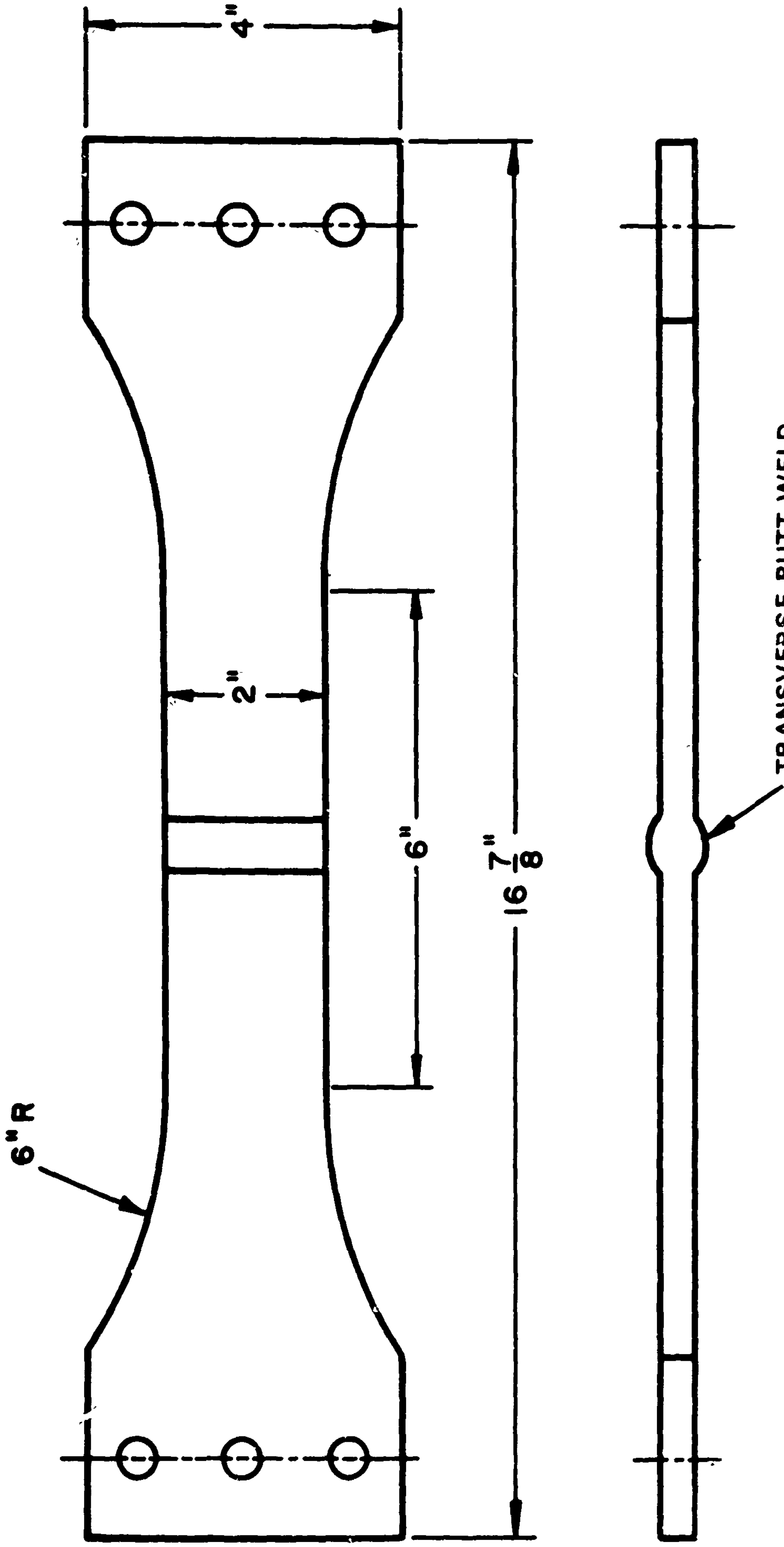
NOTES:

1. SPECIMEN THICKNESS GREATER THAN DECIMAL DIM (LAST No. 1st COL.) SHALL BE MACH. IN ACCORDANCE WITH THE DIM. SHOWN FOR THE NEXT HIGHER SPECIMEN THICKNESS RANGE
2. FOR SPECIMEN LAYOUT ALLOW 3/16" FOR SAWCUT AND FINISH OF EDGES.

SPECIMEN DIMENSIONS			
NOMINAL THICKNESS T IN	TOTAL WIDTH W_1 IN	WIDTH AT WELD W IN	MIN LENGTH L IN
3/16	2	1 1/2	20

SPECIMEN FOR FULL-SECTION TENSILE TEST OF BUTT WELD

FIG. 3-17



SPECIMEN FOR AXIAL FATIGUE TEST OF BUTT WELDS

FIG. 3-18

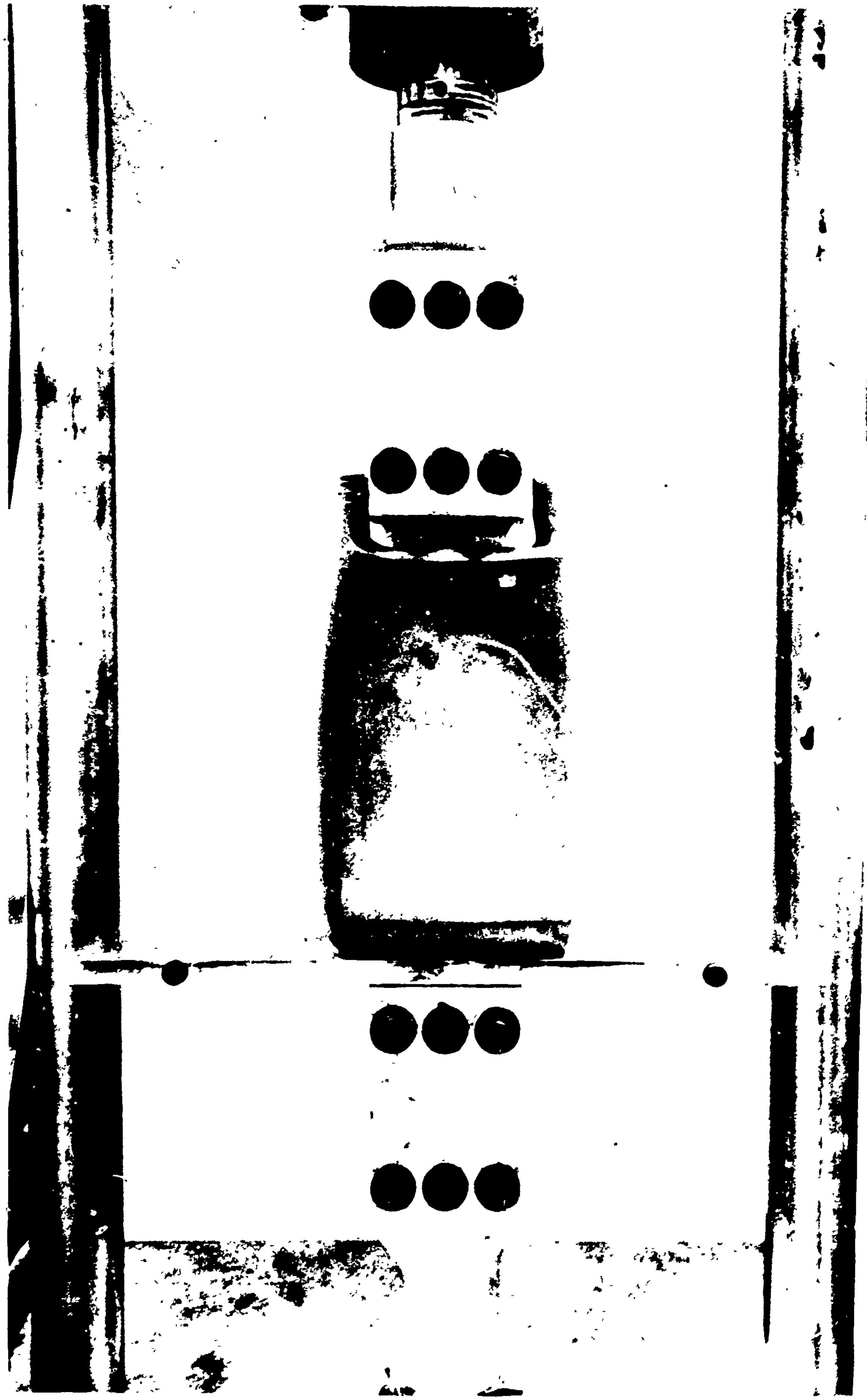


Figure 3-19 - Fatigue Tests in Sea Water

Section 4 - Results of Evaluation

4.1 X-ray Examinations - X-ray examinations of all butt-welded panels showed that the final panels had no indicated defects nor did they have large amounts of porosity. Therefore, it was not considered necessary to include records in this report.

4.2 Ultrasonic Inspection - Ultrasonic indications of weld penetration were obtained for all "tee" stiffened panels submitted for evaluation. The ultrasonic evaluation indicated that the degree of penetration was fairly constant along the length of the specimens, and that there was not much variation among specimens of a given process. Details of the inspection techniques and results of measurements are given in Appendix A.

4.3 Distortion Measurements - Tables 4-1 to 4-5 summarize out-of-plane distortions and shrinkage measurements determined for the stiffened panels. Longitudinal bow, angular distortion of the sheet relative to the extrusion and twist of the panel over its length were chosen as significant items for comparison. Because of the relative difficulty in obtaining panels made by the explosion welding process, shrinkage measurements for this case were not available. A negative value for the change in length in the tables indicates a shortening of the part, a positive value corresponds to a lengthening. A positive value of bow is shown in the sketch on Table 4-1. In two processes, high frequency resistance and explosion welding, panels used for the measurements were 36-in. long. They were cut to this length from larger panels to facilitate their use in subsequent testing. Otherwise, panels were 48-in. long. The difference in length must be considered in comparing values of longitudinal shrinkage, bow and twist of the panels.

Out-of-plane distortions for the butt welded panels are summarized in Table 4-6. Positive values of bow are shown in the sketches. Shrinkage data obtained are given in Table 4-7. The negative values indicate shortening of the part.

4.4 Residual Stress Measurements - The results of residual stress determinations for the stiffened panels are shown in Figs. 4-1 to 4-5. The data from mechanical strain measurements (see Figs. 4-1 and 4-2) were essentially the same as those from electrical resistance strain gages. Figs. 4-6 to 4-8 give the results for the butt-welded panels. In this case data are given for both surfaces since there were considerable changes of strain through the thickness.

4.5 Hardness Measurements - Figs. 4-9 to 4-13 show representative hardness surveys taken for the stiffened panels. Hardness determinations for the butt-welded panels are given in Fig. 4-14.

4.6 Corrosion Test Results

4.6.1 Accelerated Exfoliation Tests - The results of the ASSET exfoliation test indicated excellent resistance to exfoliation. Fig. 4-15 shows butt-welded panels after exposure in the as-welded condition. The butt-welded specimens heated 1 week at 212 F are shown in Fig. 4-16.

4.6.2 Stress Corrosion Tests - Table 4-8 presents the results of stressed beam assemblies of both fillet weldments and butt-welded sheet. The three best processes only were evaluated for the stiffened panels; thus results for panels made by electron beam and explosion welding are not shown.

4.7 Static and Fatigue Tests - Tensile properties of the base material from coupons cut from the panels obtained for final evaluation are given in Table 4-9. Table 4-10 summarizes the results of the static bending tests of stiffened panels. The yield strength was determined from the stress-strain curves obtained during tests. Fig. 4-17 shows a representative stress-strain curve with a line corresponding to the 0.2 per cent offset strain used to define yield strength. In some cases the specimen deflected to the limit of the clearance allowed in the test setup without failure of the part. One panel after test is illustrated in Fig. 4-18.

Table 4-11 summarizes the flexural fatigue tests of the stiffened panels. The log mean lives indicated were obtained by taking the anti-log of the average of the logs of the lives obtained in each test.

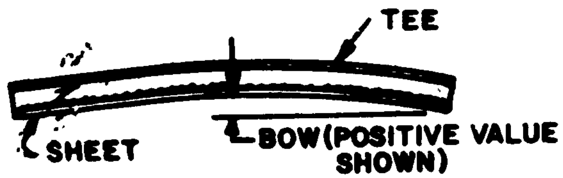
The results of static tests of butt-welded panels are shown in Table 4-12. Yield strength values were obtained based upon the 0.2 per cent offset strain in a 10-in. gage length. The elongation values shown are also based upon a 10-in. gage length. Table 4-13 provides a summary of the axial stress fatigue tests of the transverse butt-welded specimens. Results were obtained from tests both in air and in sea water environments.

4.8 Metallographic Examinations - Figs. 4-19 to 4-23 show representative photomacrographs of the joint in the stiffened panels. Figs. 4-24 to 4-27 give similar studies of the welds in the butt-welded panels.

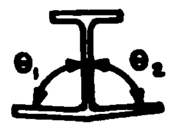
TABLE 4-1

SUMMARY OF DISTORTION MEASUREMENTS OF
STIFFENED PANELS-CONVENTIONAL GMAW

Spec. No.	Change in Length of Sheet, in. Longitudinal	Change in Length of Sheet, in. Transverse	Change in Length of Extrusions, in. Longitudinal	Out-of-Plane Distortions: Bow in Vertical Plane, in.	Out-of-Plane Distortions: Angular Distortion of Sheet at Midspan θ_1	Out-of-Plane Distortions: Angular Distortion of Sheet at Midspan θ_2	Out-of-Plane Distortions: Twist in Extrusion End to End
A-11-19-3	-.053	+.004	-.004	.008	89°52'	89°15'	0°9'
A-11-20-1	-.040	+.005	-.003	.018	90°2'	89°19'	1°5'
A-11-20-2	-.042	+.004	0	.014	89°9'	90°10'	0°5'
A-11-20-4	-.047	+.004	-.001	.006	89°25'	89°52'	1°11'
A-11-20-9	-.041	+.004	-.019	.017	88°43'	90°39'	0°47'
A-11-22-1	-.043	-.005	-.004	.013	90°16'	88°43'	0°13'
A-11-22-2	-.045	-.003	-.001	.008	90°24'	88°38'	0°42'
A-11-22-4	-.041	-.003	+.001	.013	88°32'	90°29'	0°27'
A-11-22-3	-.036	-.004	-.004	.013	90°20'	88°57'	0°3'
A-11-25-4	-.043	-.003	-.007	.013	89°38'	89°3'	0°38'
A-11-25-3	-.055	-.003	-.004	.005	90°10'	88°26'	0°3'
A-11-25-2	-.048	-.003	-.005	.002	89°7'	89°38'	0°21'



LONGITUDINAL BOW



ANGULAR DISTORTIONS

Note: Longitudinal shrinkage based upon 47-1/2" gage length. Transverse shrinkage ... width of sheet (approximately 3.75"). Bow is for 48-in. long specimen.

TABLE 4-2

SUMMARY OF DISTORTION MEASUREMENTS OF
STIFFENED PANELS-PULSED GMAW

Spec No.	Change in Length of Sheet, in.		Change in Length of Extrusions, in.	Out-of-Plane Distortions			
	Longitudinal	Transverse	Longitudinal	Bow in Vertical Plane, in.	Angular Distortion of Sheet at Midspan θ_1	Angular Distortion of Sheet at Midspan θ_2	Twist in Extrusion End to End
E-11-5-1	-.052	-.005	-.002	.060	86° 38'	89° 38'	0° 50
E-11-5-2	-.057	-.009	-.002	.074	85°55'	90°16'	0°48'
E-11-5-3	-.058	-.006	-.001	.094	87° 07'	88° 59'	0° 36'
E-11-5-4	-.049	-.008	0	.059	86°36'	89°48'	0°51'
E-11-5-5	-.061	-.007	+.004	.092	86°16'	90°00'	1°37'
E-11-5-6	-.059	-.003	-.006	.094	87°11'	89°01'	0°58'
E-11-5-7	-.056	0	-.004	.092	86°32'	90°00'	0°40'
E-11-5-8	-.051	-.010	-.002	.032	86°02'	90°37'	0°46'
E-11-5-9	-.056	+.001	0	.083	87°19'	88°59'	0°49'
E-11-5-10	-.053	-.004	0	.091	85°45'	90°31'	0°31'
E-11-5-11	-.051	+.001	-.010	.081	85°55'	90°08'	0°44'
E-11-5-12	-.048	+.004	-.005	.074	87°03'	89°11'	1°15'

TABLE 4-3

SUMMARY OF DISTORTION MEASUREMENTS OF STIFFENED PANELS
HIGH FREQUENCY RESISTANCE WELDS

Specimen No.	Change in Length of Sheet, in. Longitudinal	Out-of-Plane Distortions: Bow in Vertical Plane in.	Angular Distortion of Sheet at Midspan θ_1	Angular Distortion of Sheet at Midspan θ_2	Twist in Extrusion, End to End
H-12-11-1	-	.244	89°18'	89°35'	0°12'
H-12-11-3A	-	.371	88°51'	88°13'	1°00'
H-12-11-3B	-	.228	89°41'	89°08'	0°03'
H-12-11-6	-	.279	87°45'	90°06'	0°50'
J-12-11-1A	-	.277	89°48'	88°44'	0°24'
J-12-11-1B	-	.260	90°15'	88°42'	0°20'
J-12-11-2	-	.268	89°45'	88°40'	0°48'
J-12-11-3A	-	.267	89°51'	89°45'	0°36'
J-12-11-3B	-	.289	89°08'	89°22'	0°11'
J-12-11-4	-	.276	88°48'	89°46'	0°06'
H-12-18-1A	-	.289	89°42'	89°08'	0°15'
H-12-18-1[a]	+0.025	-	-	-	-
	+0.015	-	-	-	-
	+0.015	-	-	-	-
H-12-18-2[b]	-0.01	-	-	-	-
	0.0	-	-	-	-
	0.0	-	-	-	-
	-0.0	-	-	-	-
	-0.01	-	-	-	-

(a) Panel made with preheat. Measurements based upon 24-in. gage length.

(b) Panel made without preheat. Measurements based upon 24-in. gage length.

TABLE 4-4

SUMMARY OF DISTORTION MEASUREMENTS OF STIFFENED PANELS IN CHAMBER-ELECTRON BEAM WELDTRUSION

Specimen No.	Change in Length of Sheet, in.		Out-of-Plane Distortions			
			Bow in Vertical Plane, in.	Angular Distortion of Sheet at Midspan		Twist in Extrusion End to End
	Longitudinal	Transverse		θ_1	θ_2	
F-11-13-1	-	-	.076	90°02'	89°47'	0°46'
F-11-13-2	-	-	.064	90°21'	89°33'	0°46'
F-11-13-3	-	-	.102	90°21'	89°39'	0°28'
F-11-13-4	-0.015	-0.01	.053	89°51'	89°51'	0°31'
F-11-13-5	-0.015	-0.005	.111	89°01'	90°5[illegible]'	0°28'
F-12-3-2	-0.005	0.0	.110	90°04'	90°11'	0°02'
F-12-3-3	-0.020	-0.005	.112	89°51'	90°00'	0°20'
F-12-3-1	-0.020	-0.005	--	-	-	--
F-12-3-4	0.0	0.0	--	-	-	--
F-12-3-7	-0.015	0.0	--	-	-	--
F-12-3-8	-0.020	-0.005	--	-	-	--
F-12-3-9	-0.010	-0.005	--	-	-	--
F-12-3-10	-0.005	-0.005	--	-	-	--
F-12-3-11	-0.015	-0.010	--	-	-	--
F-12-3-12	-0.020	0.0	--	-	-	--

Note: 48-in. long specimens.

TABLE 4-5

SUMMARY OF DISTORTION MEASUREMENTS OF STIFFENED PANELS
EXPLOSION WELDS

Specimen Number	Bow in Vertical Plane, in.	Angular Distortion of Sheet at Midspan		Twist in Extrusion End to End
		θ_1	θ_2	
N-3-19-1	0.287	92°-0'	90° 30'	-
N-3-19-2	0.285	90° 10'	91° 54'	0° 38'
N-3-19-3	0.231	91°-9'	90° 57'	0° 11'
N-3-19-4	0.314	92° 8'	90° 12'	0° 0'

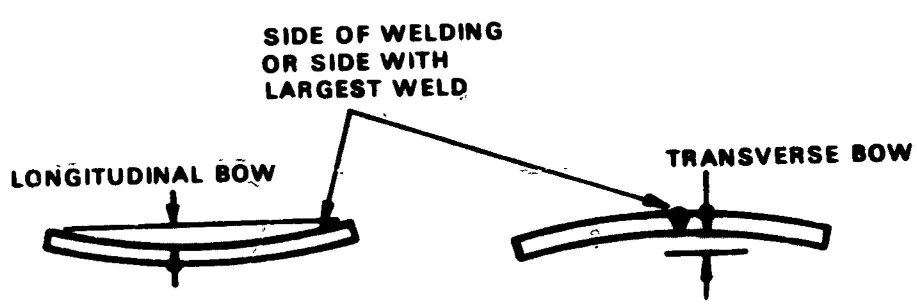
Note: 36-in. long panels.

TABLE 4-6

OUT-OF-PLANE DISTORTION OF BUTT-WELDED PANELS

Weld Process	Specimen Number	Longitudinal Bow at Midwidth, in.	Transverse Bow at Midlength[e]
Conventional GMAW[a]	L-2-6-2[b]	0.67	0.11
	L-2-6-3[b]	0.72	0.13
	L-2-7-1[c]	0.91	0.20
	L-2-7-2[c]	0.89	0.21
Plasma GMAW[d]	G-12-2-6	0.16	0.14
	G-12-2-8	0.15	0.13
	G-12-2-10	0.15	0.15
Sliding Seal Electron Beam Welding[a]	M-12-17-1	0.06	0.04
	M-12-17-1	0.23	0.08

(a) 20" wide x 50" long panels.
(b) Welded one side.
(c) Welded both sides.
(d) 20" wide x 20" long panels.
(e) Transverse bow in opposite direction to longitudinal bow.



SKETCHES SHOWING POSITIVE BOW

TABLE 4-7

SHRINKAGE IN BUTT-WELDED PANELS[a]

Specimen Number	Weld Procedure	Change in Length at Midwidth, in.[b]	Change in Width at Midlength, in.[c]
	Conventional GMAW		
L-2-6-2	Welded from one side	-0.014	-0.033
L-2-6-3	Welded from one side	-0.017	-0.028
L-2-7-1	Welded from both sides	-0.069	-0.031
L-2-7-2	Welded from both sides	-0.066	-0.033
	Sliding Seal Electron Beam		
M-12-17-1	-	0.0	0.0
M-12-17-2	-	0.0	-0.002
M-12-17-3	-	0.0	-0.002
M-12-17-4	-	-0.004	0

(a) Panels were nominally 20" wide x 50" long.
(b) Measured over 49-1/4" length for conventional GMAW, 39.4 in. for sliding seal EB welds.
(c) Measured over 19-1/2" width for conventional GMAW, 19-in. for sliding seal EB welds.

TABLE 4-8

RESISTANCE TO STRESS-CORROSION CRACKING OF 5456-ALLOY WELDED BEAM ASSEMBLIES EMPLOYING VARIOUS WELD PROCESSES AND EXPOSED TO 3-1/2% NaCl SOLUTION BY ALTERNATE IMMERSION

Weld Process	As Welded			Heated 1 Week @ 212 F		
	Date Exposed	F/N(3)	Days To Fail	Date Exposed	F/N(3)	Days To Fail
Fillet Weldments of 5456-H111 Extruded Tee Welded to 5456-H116 Sheet(1)(2)						
Pulsed GMAW	2/12/75	0/2	OK-114	2/12/75	0/2	OK-114
Conventional GMAW	2/12/75	0/2	OK-114	2/12/75	0/2	OK-114
Hi-Frequency Resistance	2/12/75	0/2	OK-114	2/12/75	0/2	OK-114
Butt-Welded 5456-H116 Sheet(2)						
None (Sheet)	3/24/75	0/2	OK-74	3/24/75	0/2	OK-74
Conventional GMAW	3/24/75	0/2	OK-74	3/24/75	0/2	OK-74
Plasma GMAW	3/24/75	0/2	OK-74	3/24/75	0/2	OK-74
Sliding Seal Electron Beam	3/24/75	0/2	OK-74	3/24/75	0/2	OK-74

Notes:
(1) .500" thick 6061 plate was bolted to extruded tee before stressing to prevent the web from buckling.

(2) All specimens were stressed to 75% of minimum guaranteed yield strength of 5456-H116 sheet (33,000 psi) - applied stress 24,750 psi.

(3) F/N = Number of specimens failed and number of stressed beam assemblies exposed.

TABLE 4-9

TENSILE PROPERTIES OF 5456-H116 SHEET
AND 5456-H111 EXTRUSIONS

(Base Metal)

Source and Product	Direction	Yield Strength, ksi	Tensile Strength, ksi	Elongation in 2 in., %
Cut from Butt-Welded Panels (3/16-in. thick)				
Conventional GMAW-sheet	L	38.3	52.1	13.5
	T	34.9	52.1	17.0
Plasma GMAW-sheet	L	40.6	53.3	13.0
	T	36.2	52.6	16.0
Slidir al Electron Beam-sheet	L	38.8	52.3	13.0
	T	35.2	52.4	16.5
Cut from Stiffened Panels				
Conventional GMAW-sheet	L	38.3	54.2	12.5
extrusion(a)	L	29.0	46.1	22.0
Pulsed GMAW-sheet	L	38.2	53.6	12.0
extrusion(a)	L	28.0	46.2	23.0
Explosion-sheet	L	44.1	55.6	14.0
extrusion(a)	L	32.2	47.8	16.0
HF Resistance-sheet	L	36.1	53.5	12.0
extrusion(a)	L	27.1	44.6	19.5
In Chamber Electron Beam Weldtrusion-				
sheet	L	38.2	52.7	13.0
extrusion(a)	L	29.9	46.2	23.5
Minimum Specified Properties(b)				
5456-H116 Sheet (0.063-0.0624)		33	46	10
5456-H111 Extrusions		26	42	12

(a) Web of extrusion, 1/8-in. thick.

(b) Aluminum Standards and Data, 1974-75, The Aluminum Association.

TABLE 4-10

STATIC TESTS OF STIFFENED PANELS

Weld Process	Load at Failure, lb.	Apparent Maximum Stress at Tensile Flange, ksi	Yield Strength, ksi(b)	Approximate Deflection at Failure in.	Failure Mode
Conventional GMAW	19,400	55.1	38.4	4.7(a)	Excessive deflection
	18,900	53.7	38.2	5.0	Fracture of tensile flange
Pulsed GMAW	19,280	54.4	40.4	4.8	Fracture of tensile flange
	18,880	53.6	35.1	5.1(a)	Excessive deflection
HF Resistance	19,100	54.8	36.1	5.0(a)	Excessive deflection
	18,950	54.2	35.4	4.5(a)	Excessive deflection
Electron Beam	9,350	25.4	-- (c)	0.30	Shear in weld
	8,100	21.9	-- (c)	0.25	Shear in weld
Explosion	23,350	50.5	47.4	1.95	Shear at joint

(a) Deflection limited by clearance in test setup.

(b) Stress at 0.2% offset.

(c) Panel failed before yield strength was reached.

TABLE 4-11

FLEXURAL FATIGUE TEST OF WELDED BEAMS

R, STRESS RATIO = 0.05

	Tests in Seawater				Tests in Air			
Weld Type	Specimen Number	Maximum Stress, ksi	Cycles to Failure	Failure Origin	Specimen Number	Maximum Stress, ksi	Cycles to Failure	Failure Origin
Conventional GMAW	A-11-19-3	15.0	303,600	Pit in weld	A-12-3-1	15.0	484,500	Deep weld ripple
	11-22-3	15.1	659,300	Toe of weld	12-2-1	15.0	496,500	Deep weld ripple
	12- 2-5	15.0	403,400	Toe of weld	12-11-1	15.0	1,481,600	Large pore at edge of fusion
		l.m.l.(a)	433,C00			l.m.l.(a)	820,900	
	A-11-20-2	10.0	3,112,000	Weld surface				
	11-22-2	10.0	4,126,800	Pore .001" below surface				
	11-25-2	10.0	574,200	Porosity at weld pit				
		l.m.l.(a)	1,946,000					
H F Pulsed GMAW	E-11-5-2	10.0	2,058,200	Weld surface	E-12-12-3	14.9	767,900	
	11-5-3	10.0	1,170,700	Weld surface	12-12-4	15.0	661,900	Gouge in bottom flange
	11-5-4	10.0	3,115,000	Weld surface	12-12-5	15.0	812,500	Weld pit
		l.m.l.(a)	1,958,000			l.m.l.(a)	747,400	
In Chamber E B Weldtrusion	E-11-13-1	10.0	54,800	Weld sheared-little fusion				
	11-13-2	10.1	242,600	Weld sheared-little fusion				
	11-13-3	10.1	489,100	Weld and weld shear				
		l.m.l.(a)	186,000					
H F Resistance (As Welded)	H-12-11-1	10.0	1,301,100	Edge of fusion				
	H-12-11-1A	10.1	1,480,900	Edge of fusion				
	H-12-11-3	10.1	1,475,400	Weld flush				
		l.m.l.(a)	1,417,000					
H F Resistance (Machined Fillet)	H-12-11-3A	10.1	2,763,600	Edge of fusion	H-12-18-2A	15.0	894,500	Edge of fusion
	H-12-11-3B	10.0	1,963,200	Edge of fusion	H-12-18-2B	15.0	1,800	Essentially no fusion
	H-12-11-1B	10.0	1,919,100					
		l.m.l.(a)	2,195,300					
Explosion Welded	H-3-19-2	10.0	659,500	Surface gouge in top flange				
	3 19-3	10.0	803,200	Interface web and flange				

(a) Log mean life

TABLE 4-12

STATIC TESTS OF BUTT-WELDED PANELS

Process	Specimen Number	Area, in.^{2}	Max. Load, lb.	Max. Stress, ksi	Yield Strength, ksi(a)	Elongation in 10 in., %
Conventional GMAW	L-2-6-2-1	.322	16,150	50.2	33.9	6.6
	-2	.3225	16,550	51.3	33.5	6.0
Plasma GMAW	G-12-2-10-1	.2985	15,850	53.1	32.8	8.0
	-2	.300	15,850	52.8	32.0	8.6
Sliding Seal Electron Beam	M-2-17-1-1	.3073	16,850	54.8	35.8	9.0
	-2	.3073	16,650	54.2	35.8	8.9

(a) Based upon 10" gage length.

TABLE 4-13

AXIAL-STRESS FATIGUE TESTS OF
TRANSVERSE BUTT WELDS IN 3/16 In. 5456-H116 SHEET
R=0.0

Weld Type	Tests in Seawater				Tests in Air			
	Specimen Number	Maximum Stress, ksi	Cycles to Failure	Failure Origin	Specimen Number	Maximum Stress, ksi	Cycles to Failure	Failure Origin
Conventional GMAW	1-2	15.0	74,800	Edge of weld, root, mild weld ripple	1-1	15.0	205,600	Edge of weld root
	2-5	15.3	62,200	Edge of weld, root, mild weld ripple	2-4	15.0	103,700	Edge of weld, root, weld ripple
	2-8	15.0	52,700	Edge of weld, root, weld ripple	2-7	15.0	128,500	Edge of weld, root, mild ripple
		l.m.l.[a]	62,600			l.m.l.[a]	139,900	
	1-3	10.0	766,900	Edge of weld, root, weld ripple				
	2-6	10.0	252,400	Edge of weld, root, mild weld ripple				
	2-9	9.9	239,400	Edge of weld, root				
		l.m.l.[a]	360,700					
Plasma GMAW	2-2	10.0	457,700	Edge of weld, root	2-1	15.0	153 700	Edge of weld, root
	3-4	9.8	364,000	Edge of weld, root	2-3	15.0	245,800	Edge of weld, root
	3-6	10.0	689,500	Edge of weld, root	3-5	15.0	189,500	Edge of weld, root
		l.m.l.[a]	486,100			l.m.l.[a]	192,800	
Sliding Seal Electron Beam	1A-2	10.0	217,[illegible]	Edge of weld, face	1A-1	15.0	163,300	Edge of weld, face
	1A-4	10.0	277,700	Edge of weld, face	1A-3	15.0	225,000	Edge of weld, face
	1A-6	10.0	224,800	Edge of weld, face	1A-5	15.0	142,100	Edge of weld, face
		l.m.l.[a]	238,500			l.m.l.[a]	173,500	

(a) Log mean life

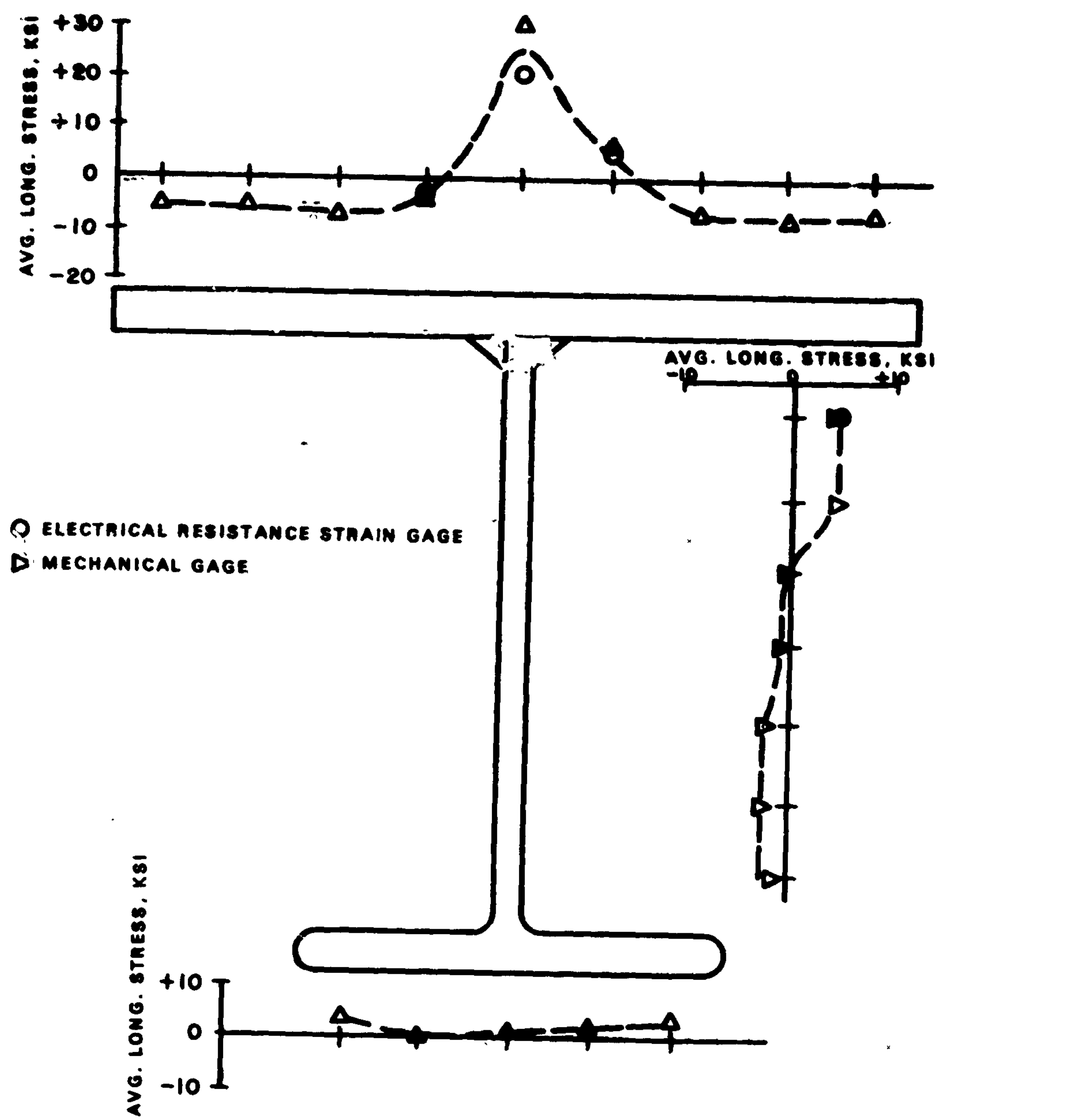


FIGURE 4-1 RESIDUAL STRESS IN STIFFENED PANEL-CONVENTIONAL GMAW

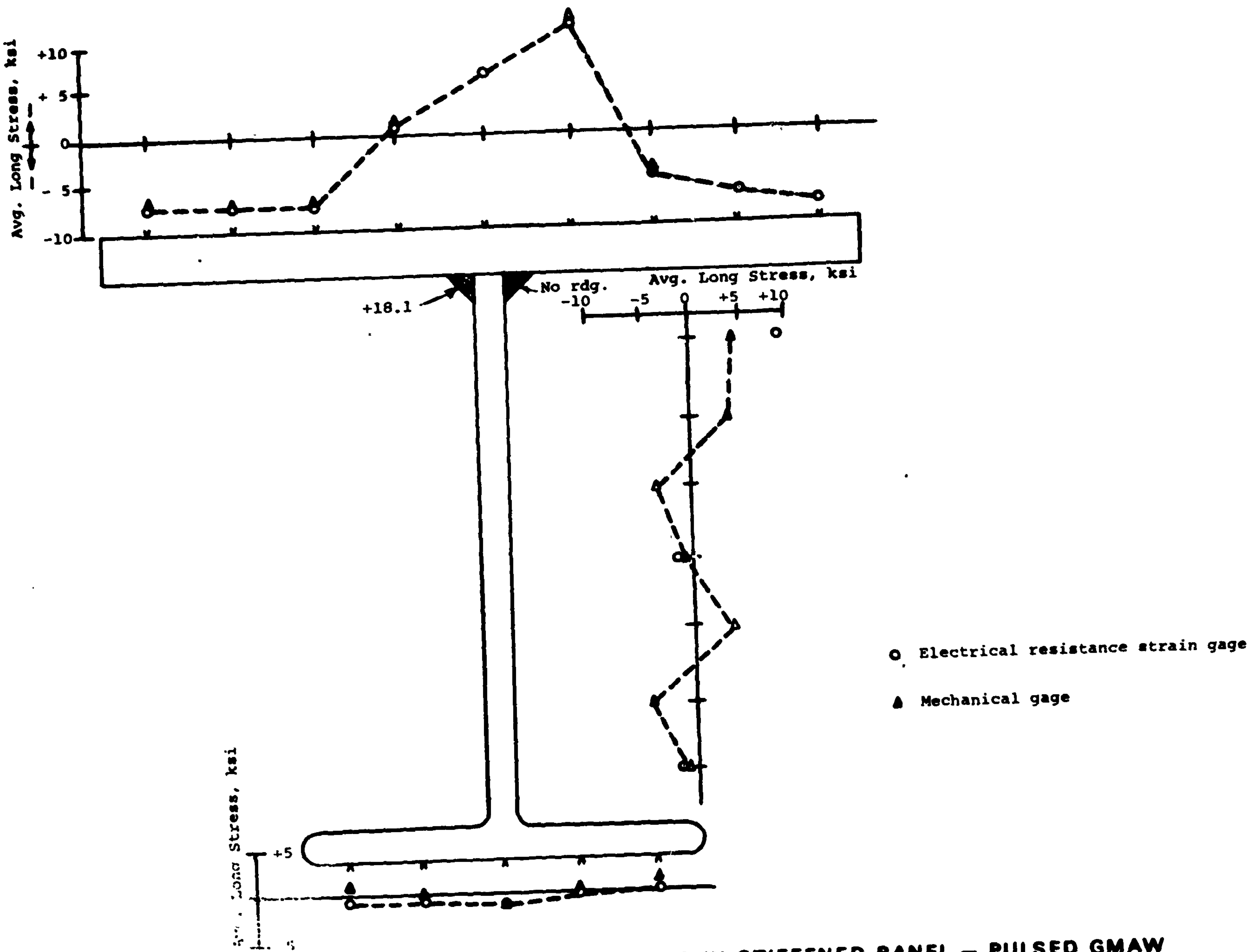


FIGURE 4-2 RESIDUAL STRESS IN STIFFENED PANEL — PULSED GMAW

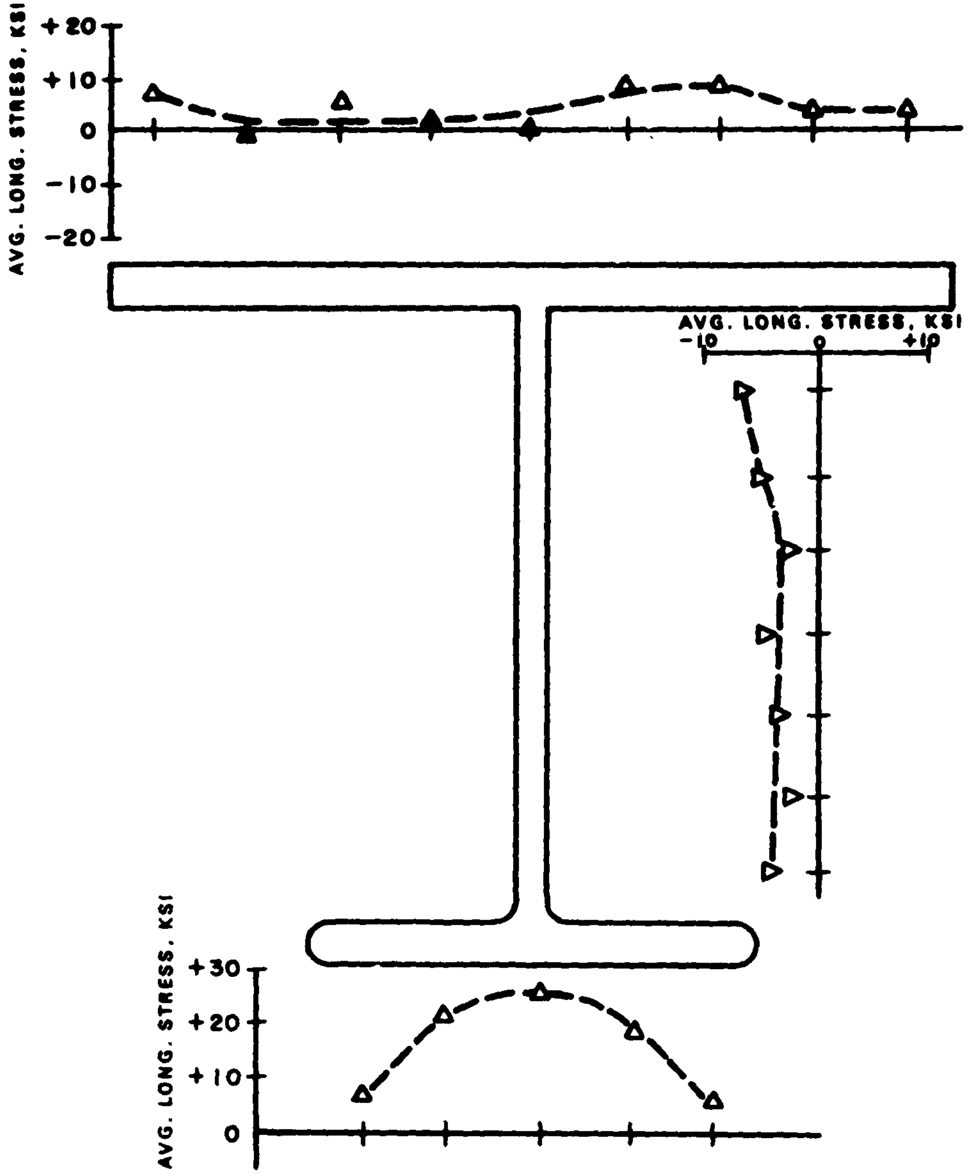


FIGURE 4-3 RESIDUAL STRESS IN STIFFENED PANEL-HF RESISTANCE WELD

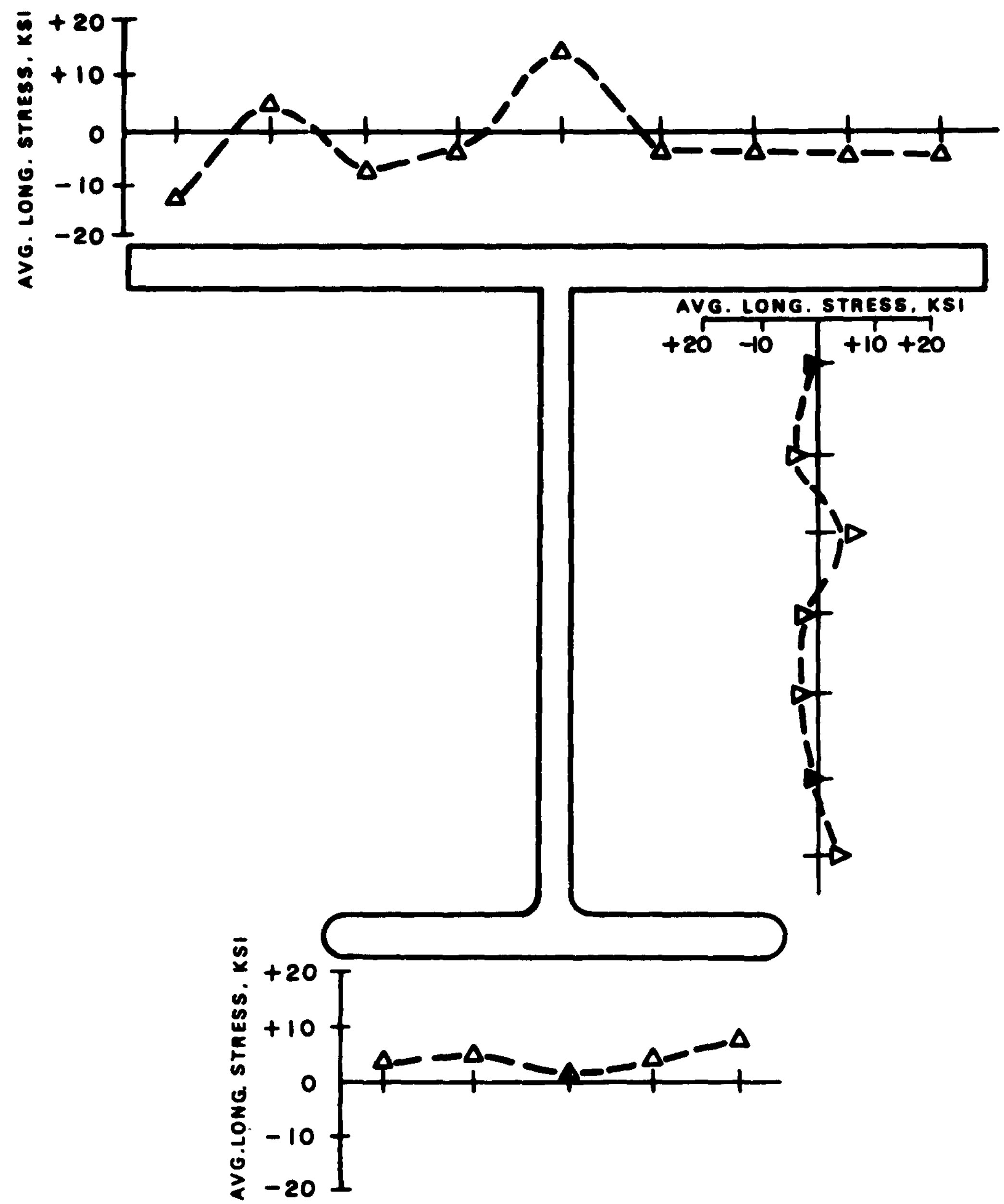


FIGURE 4-4 RESIDUAL STRESS IN STIFFENED PANEL-IN CHAMBER ELECTRON BEAM WELDTRUSION

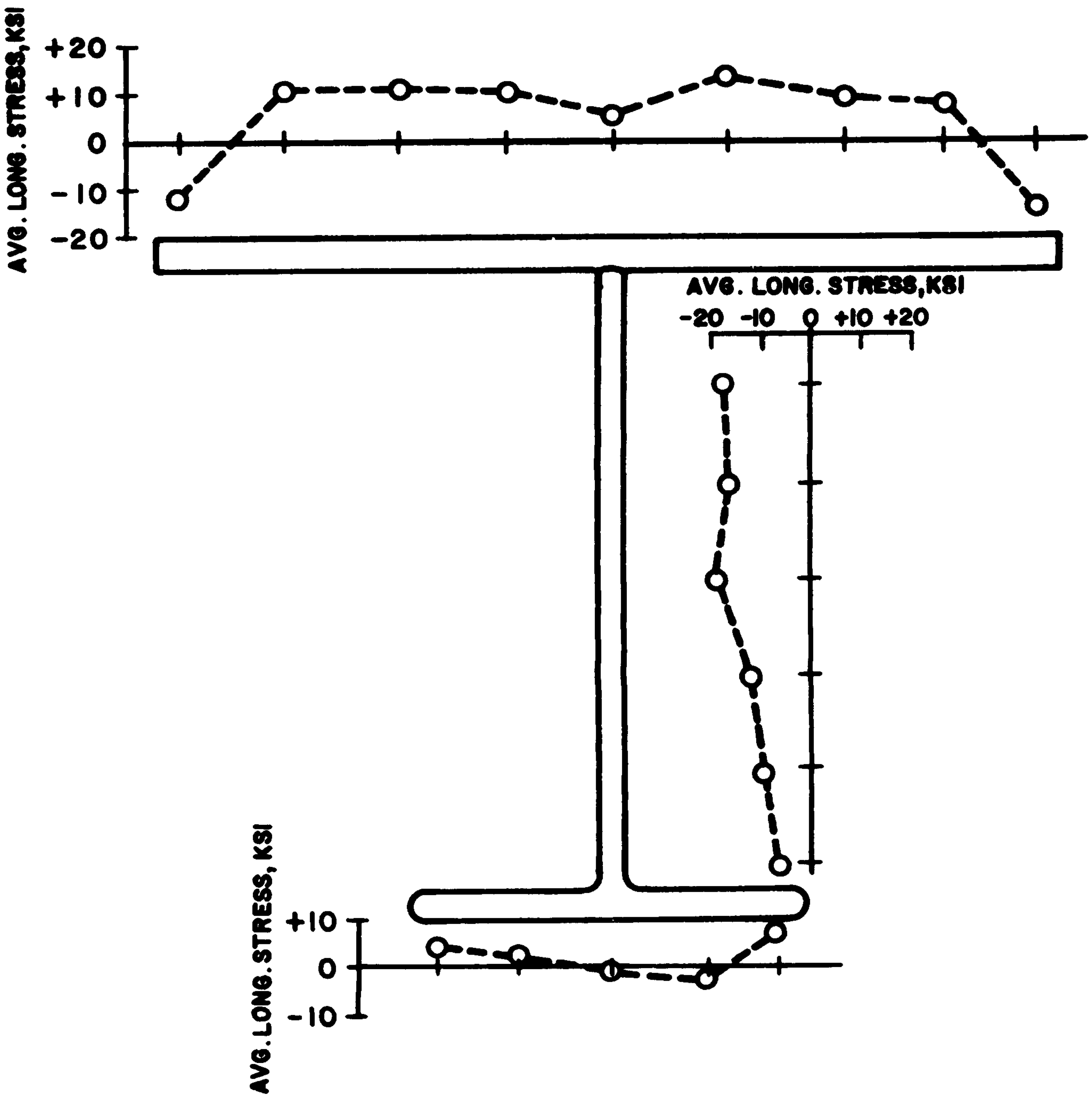


FIGURE 4-5 RESIDUAL STRESS IN STIFFENED PANEL - EXPLOSION WELD

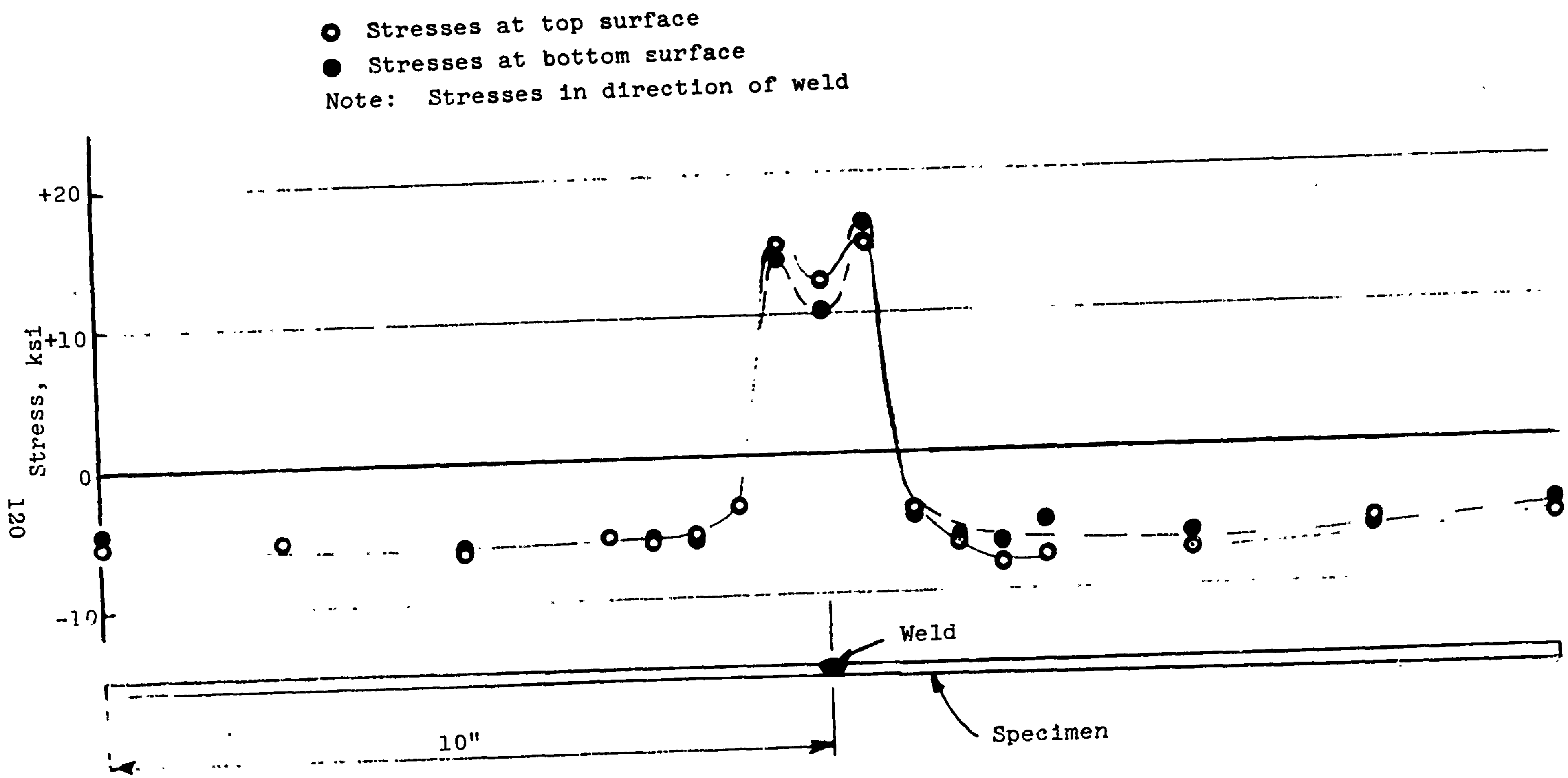


FIGURE 4-6 RESIDUAL STRESS IN BUTT-WELDED PANEL

(L-2-6-3, CONVENTIONAL GMAW)

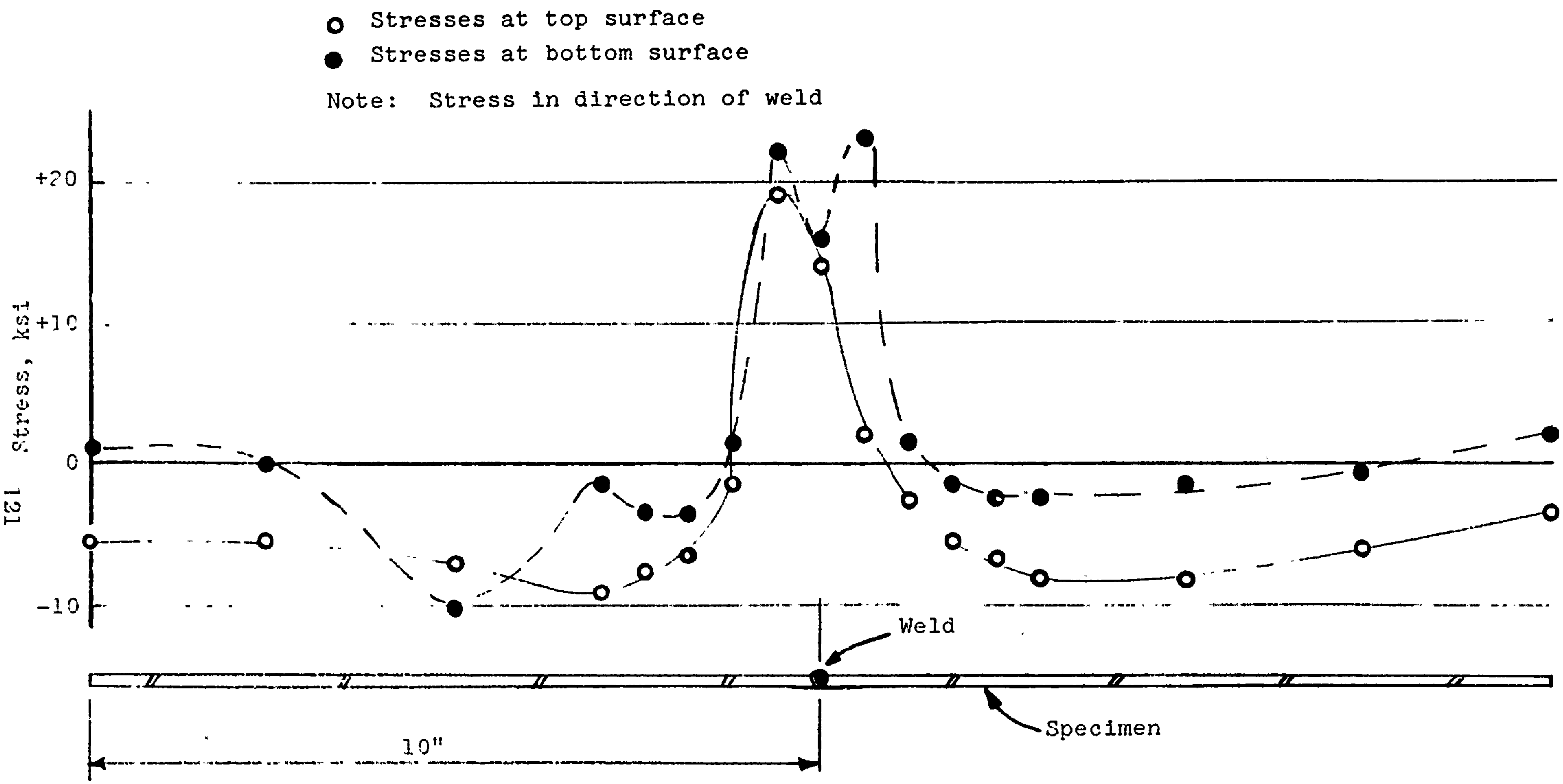


FIGURE 4-7 RESIDUAL STRESS IN BUTT WELDED PANEL

(G-12-2-8, PLASMA GMAW)

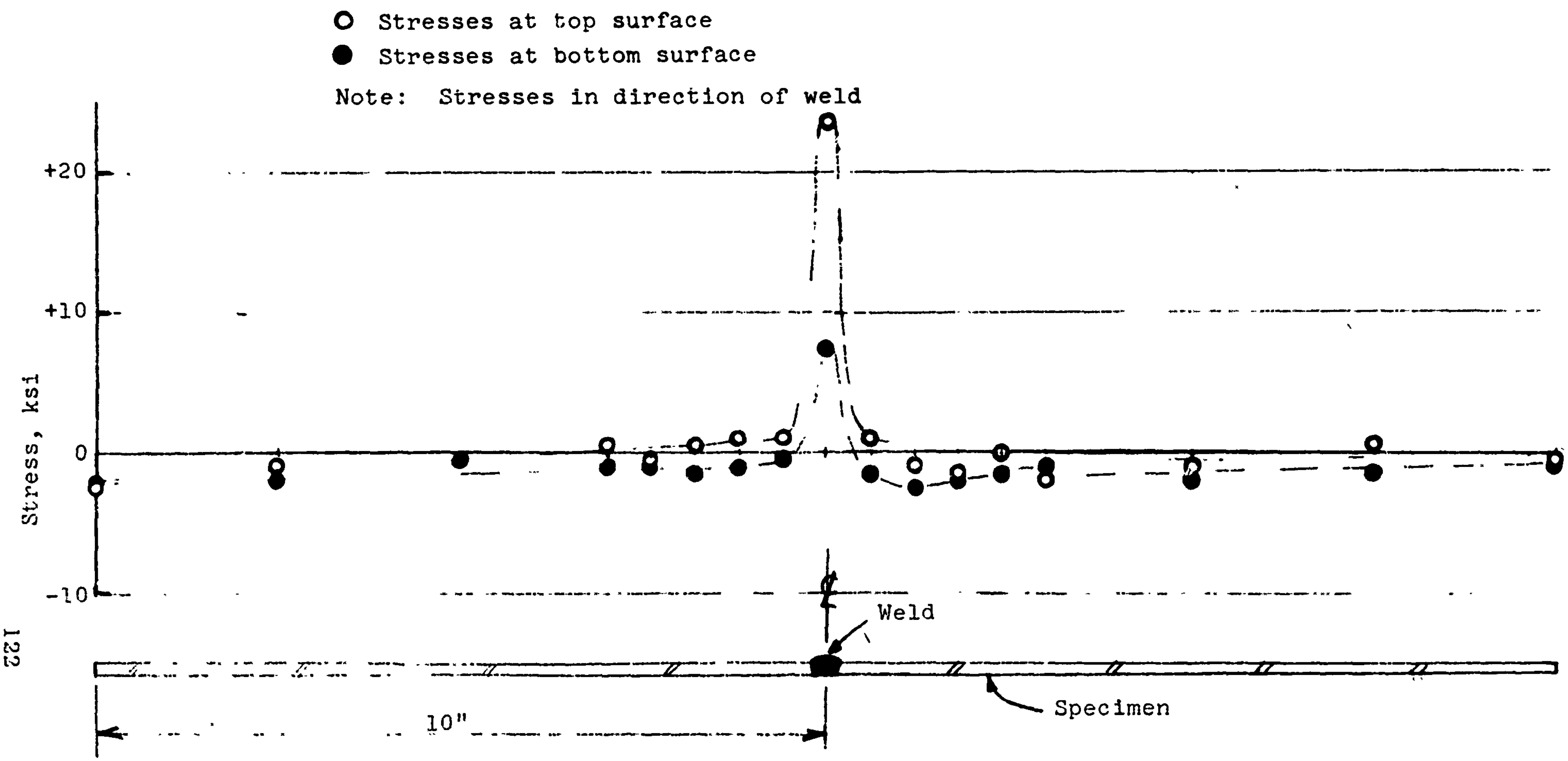
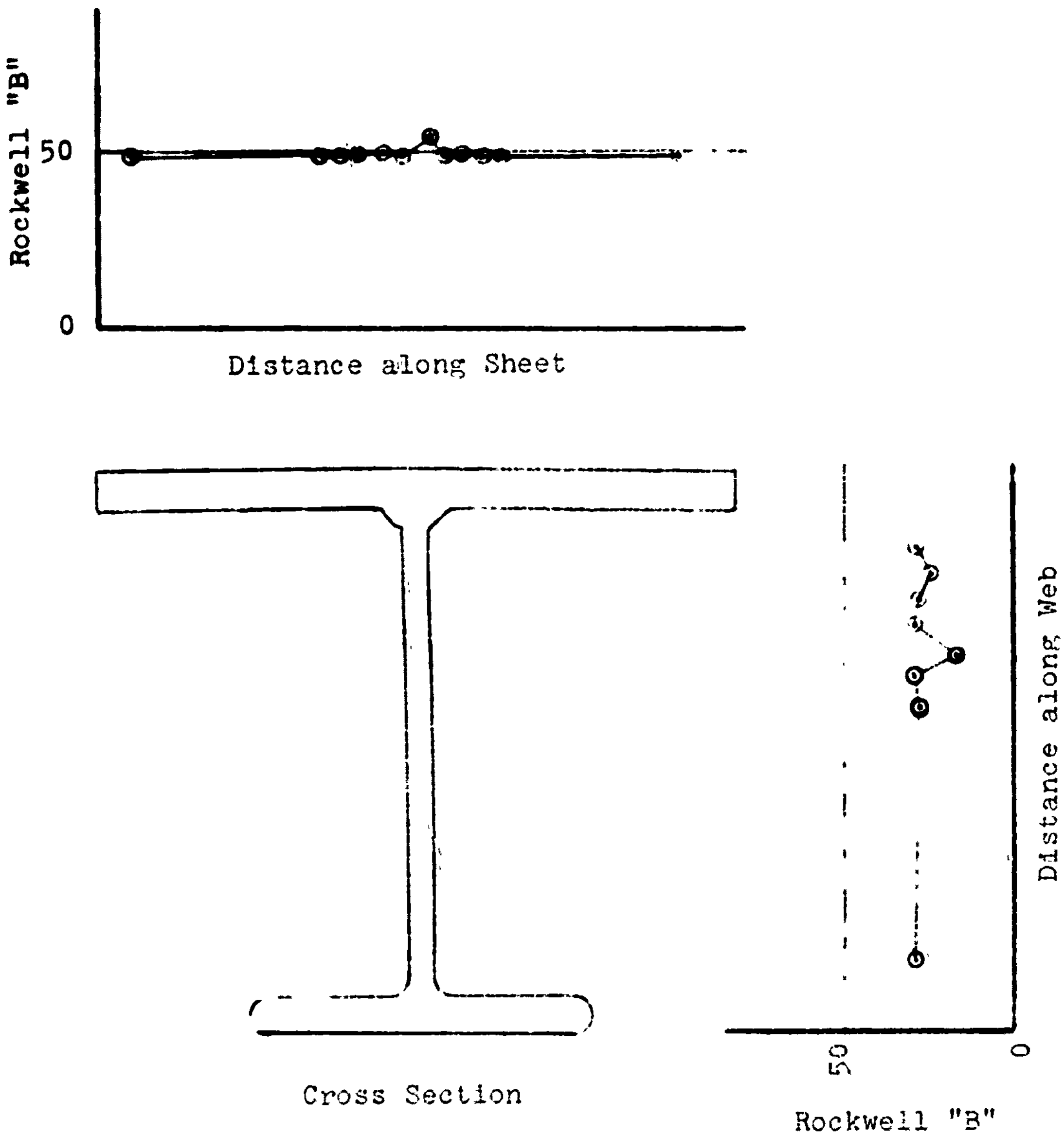


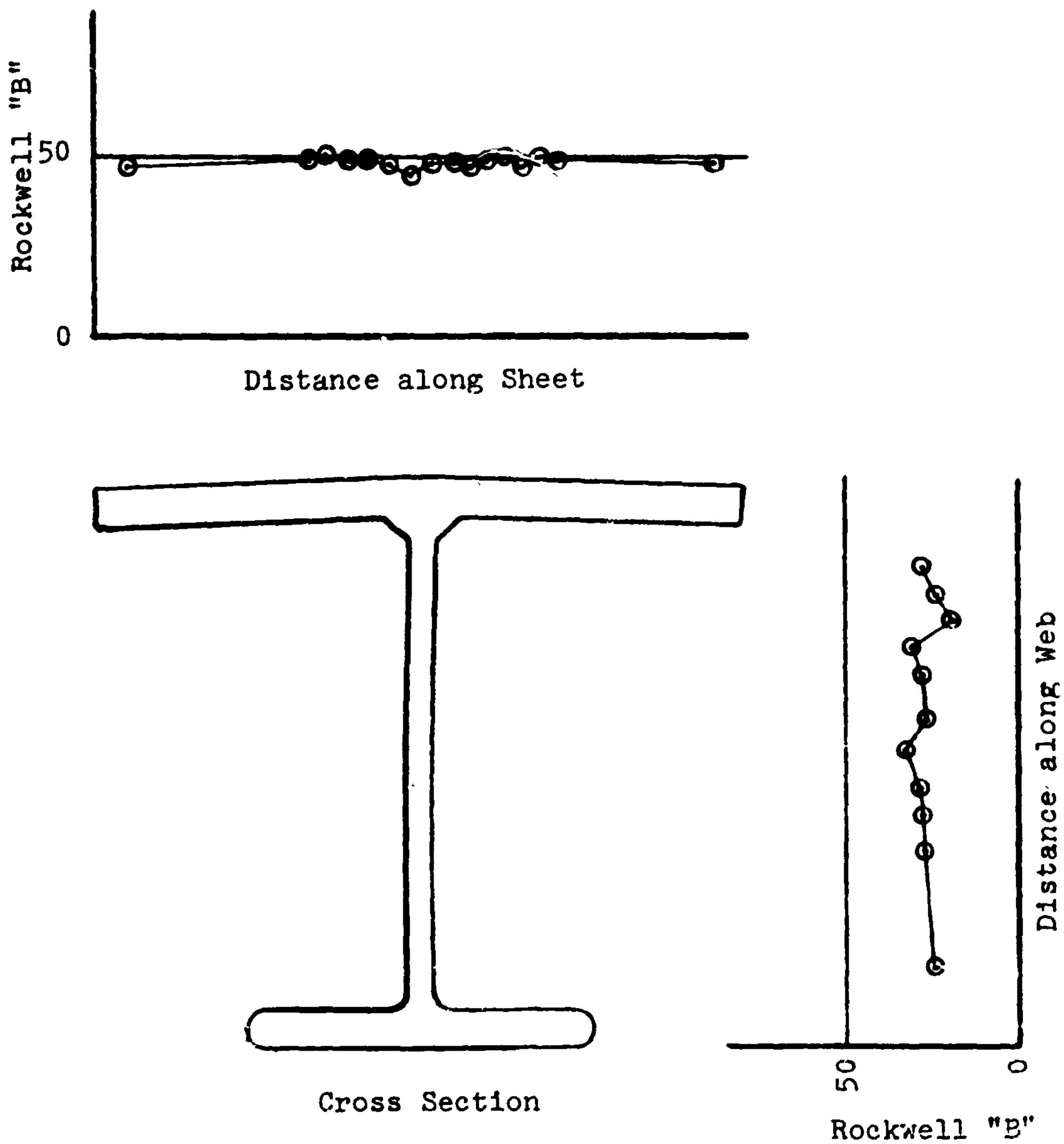
FIGURE 4-8 RESIDUAL STRESS IN BUTT-WELDED PANEL

(M-2-17-1, SLIDING SEAL ELECTRON BEAM)



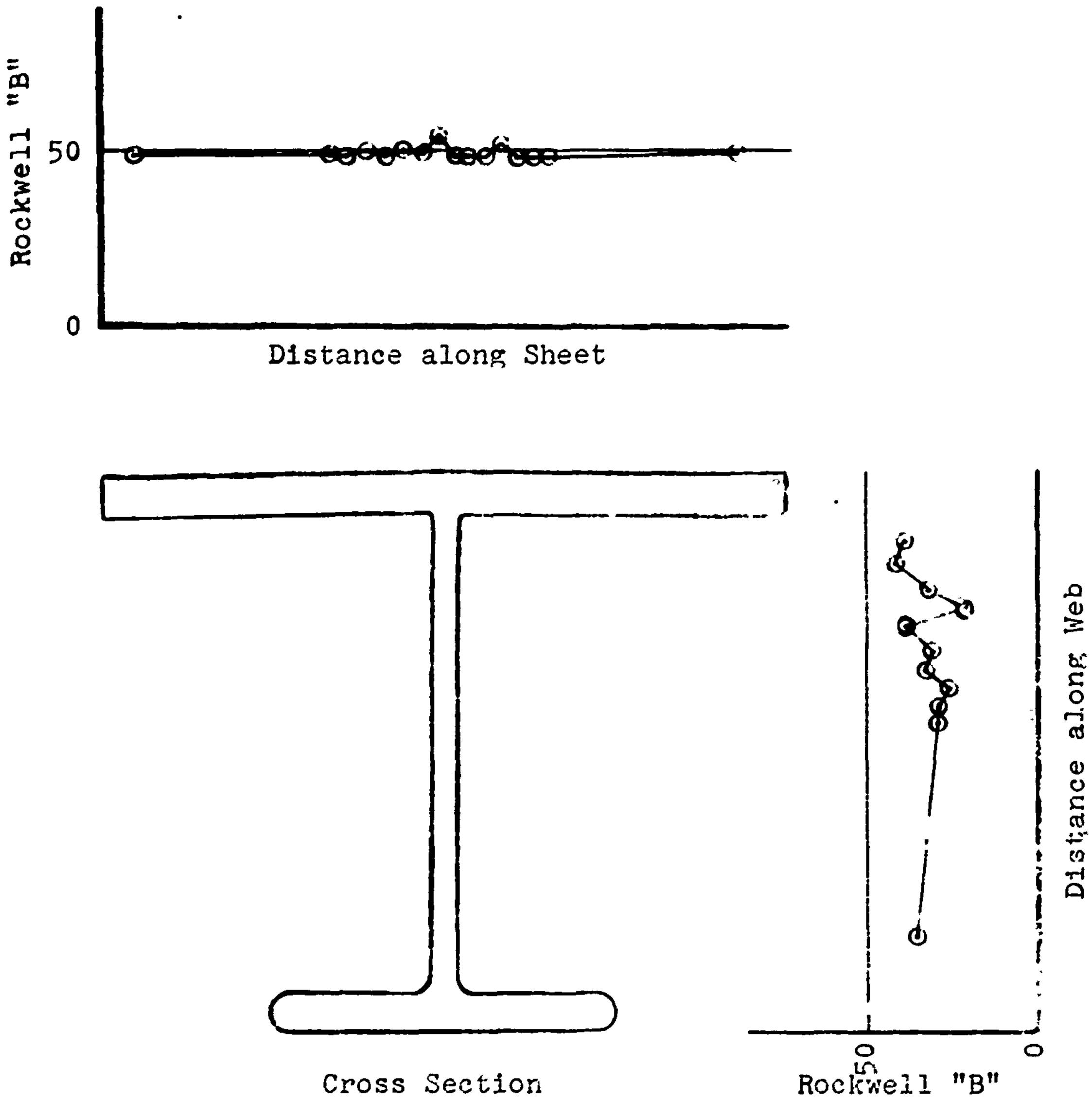
HARDNESS-CONVENTIONAL GMAW

FIGURE 4-9



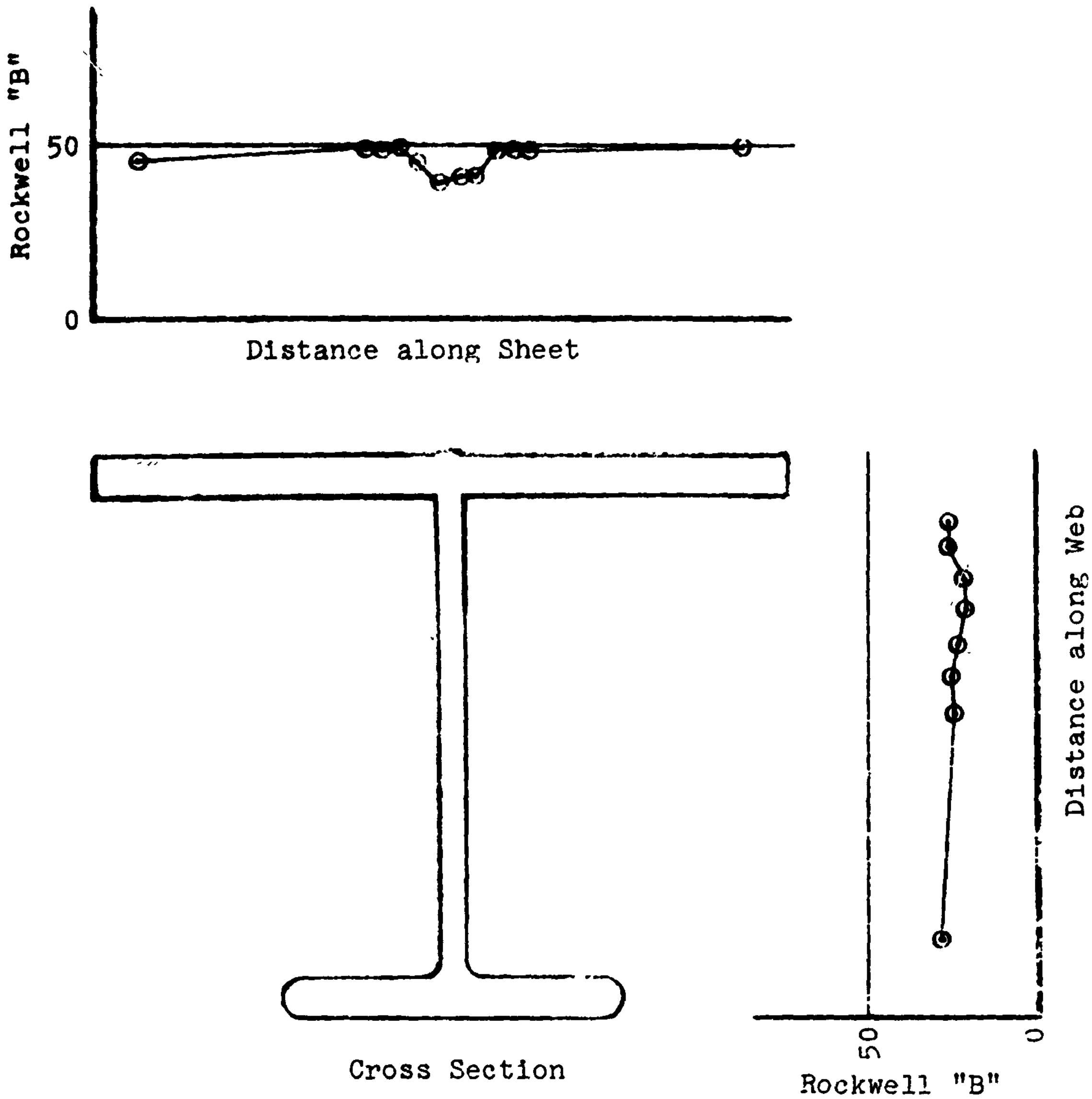
HARDNESS-PULSED GMAW

FIGURE 4-10



HARDNESS-H.F. RESISTANCE WELDING

FIGURE 4-11



HARDNESS-IN CHAMBER ELECTRON BEAM WELDTRUSION

FIGURE 4-12

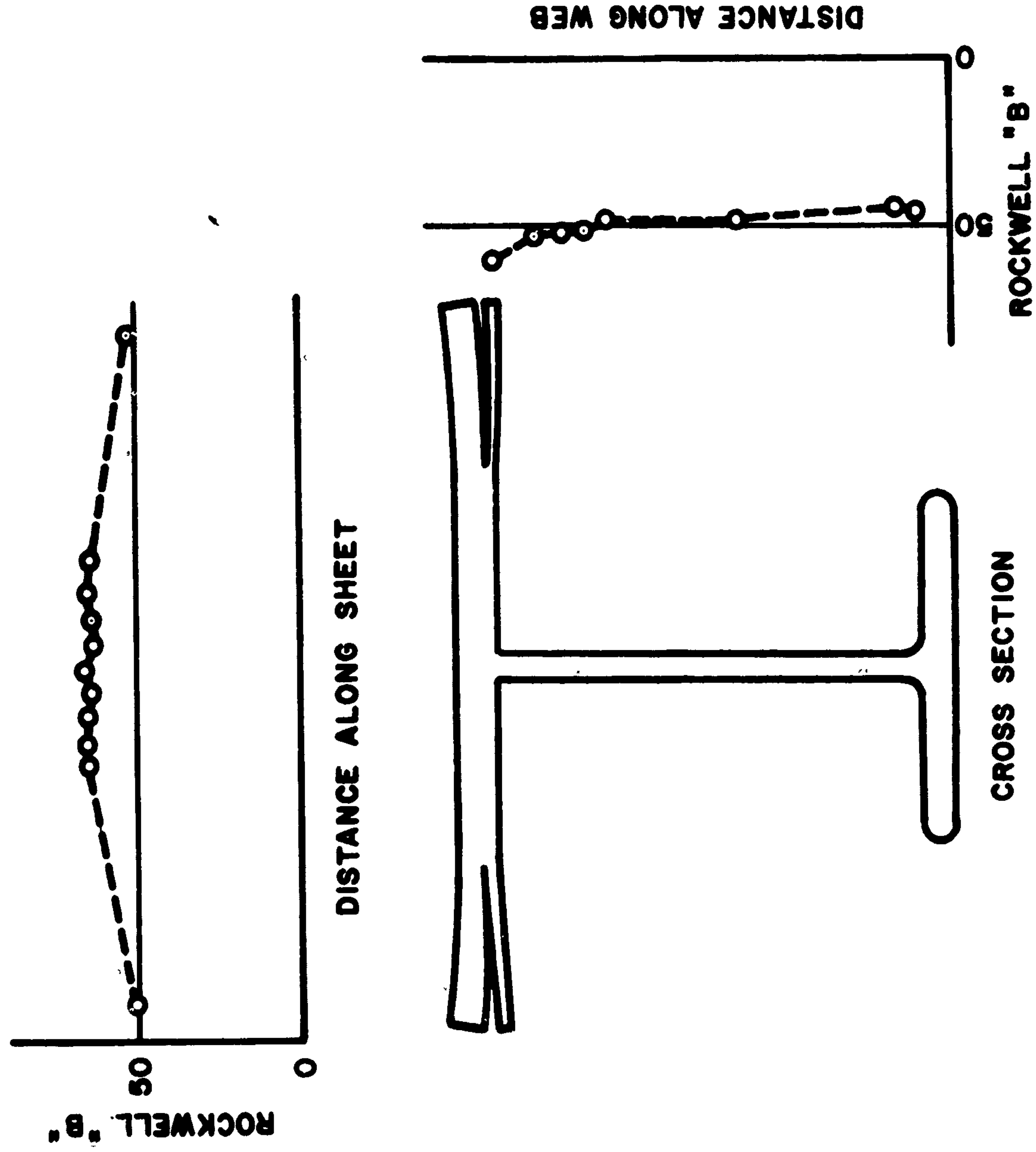


FIGURE 4-13 HARDNESS-EXPLOSION WELDING

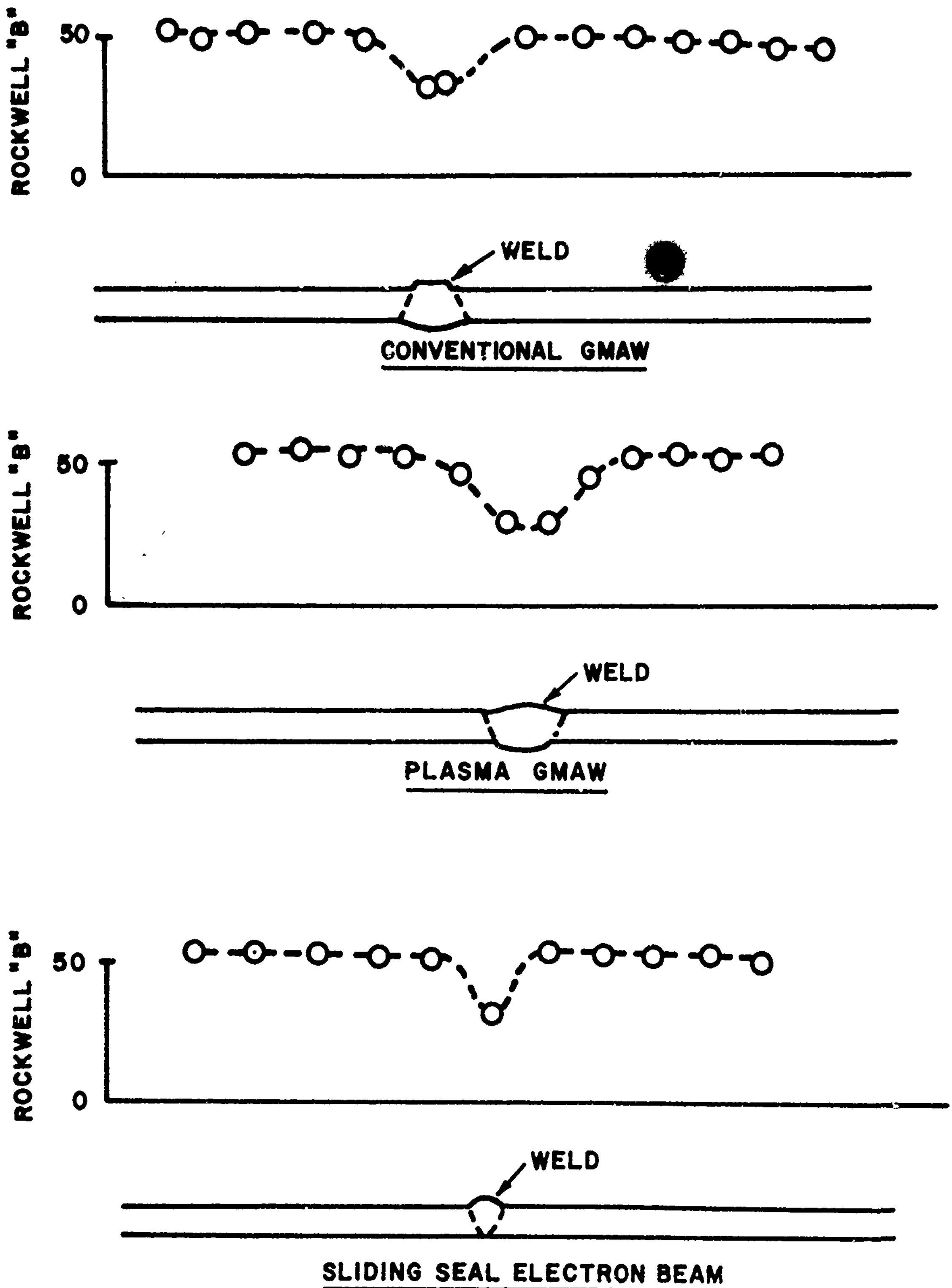


FIGURE 4-14 HARDNESS MEASUREMENTS IN BUTT WELDED PANELS

Fig. 4-15 - Corrosion Tests of Butt-Welded Panels

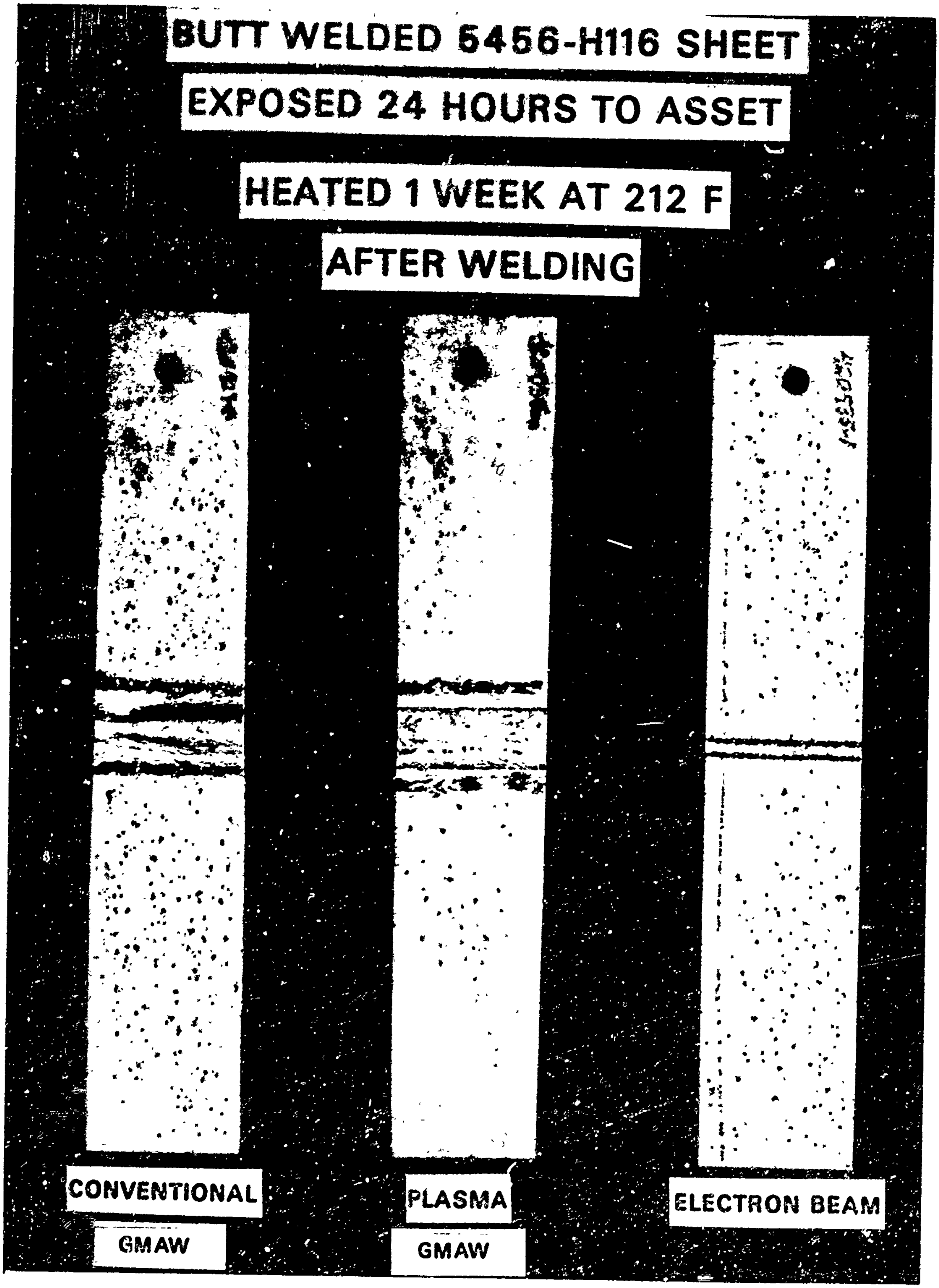
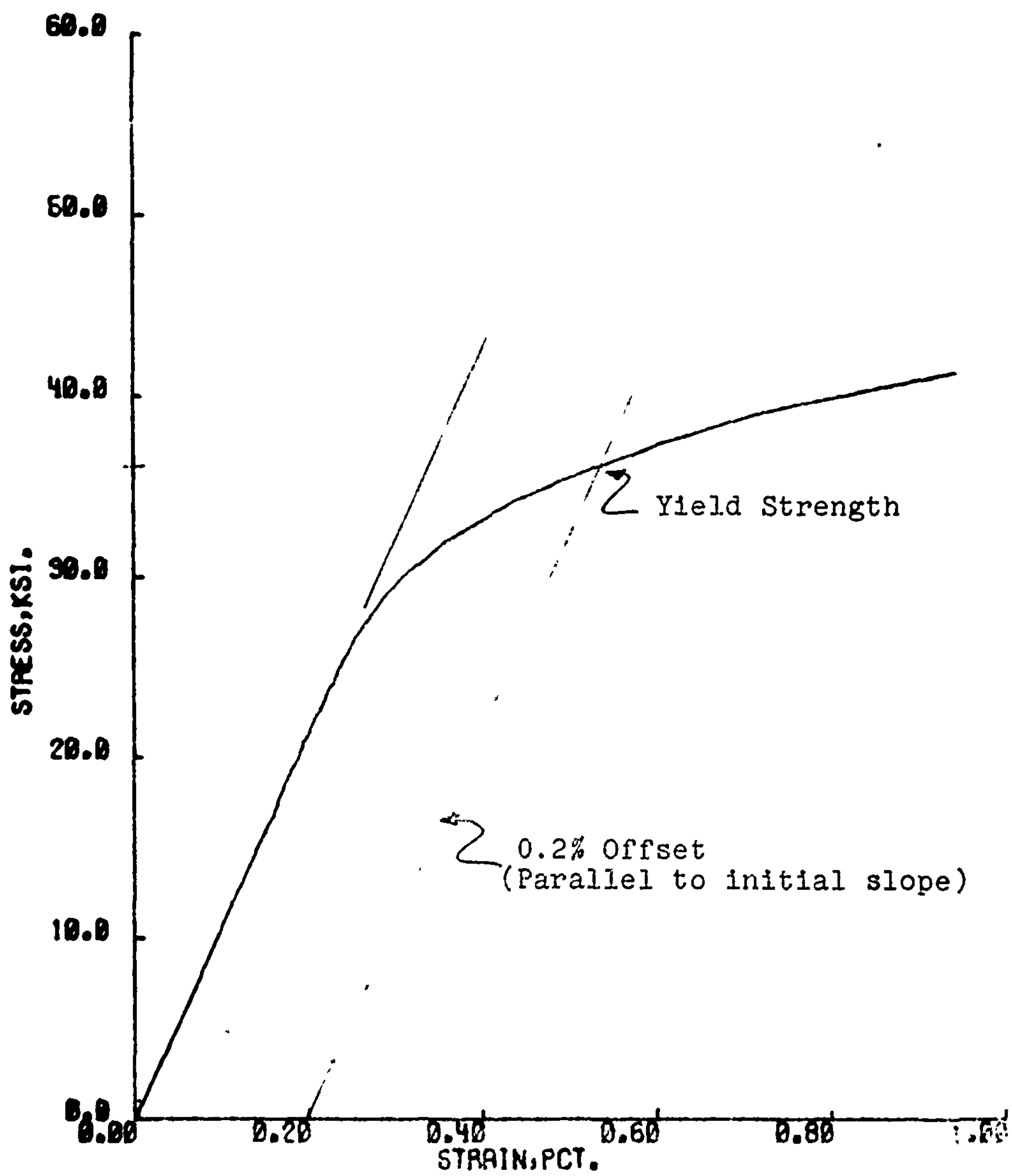


Fig. 4-16 - Corrosion Tests of Butt-Welded Panels



SPEC. NO.42D916-10 HIGH FREQ RESISTANCE WELD 1/3/75
TWO-POINT LOAD BEAM TEST

FIGURE 4-17 BEAM TEST OF STIFFENED PANEL

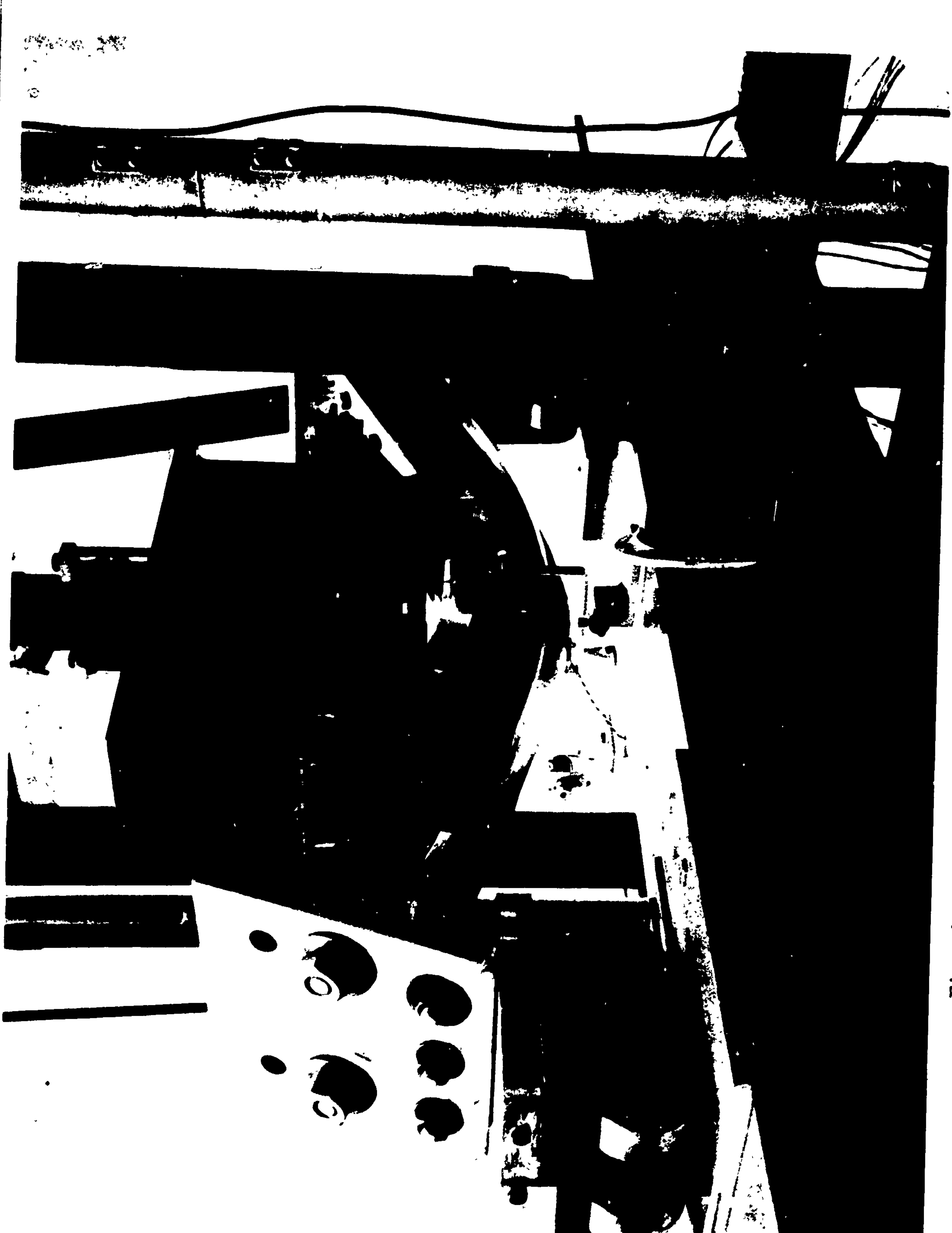


Fig. 4-18 - Failure of Specimen in Static Tests

Fig. 4-19 - Macrographs of Fillet Welds, Conventional GMAW (15X)

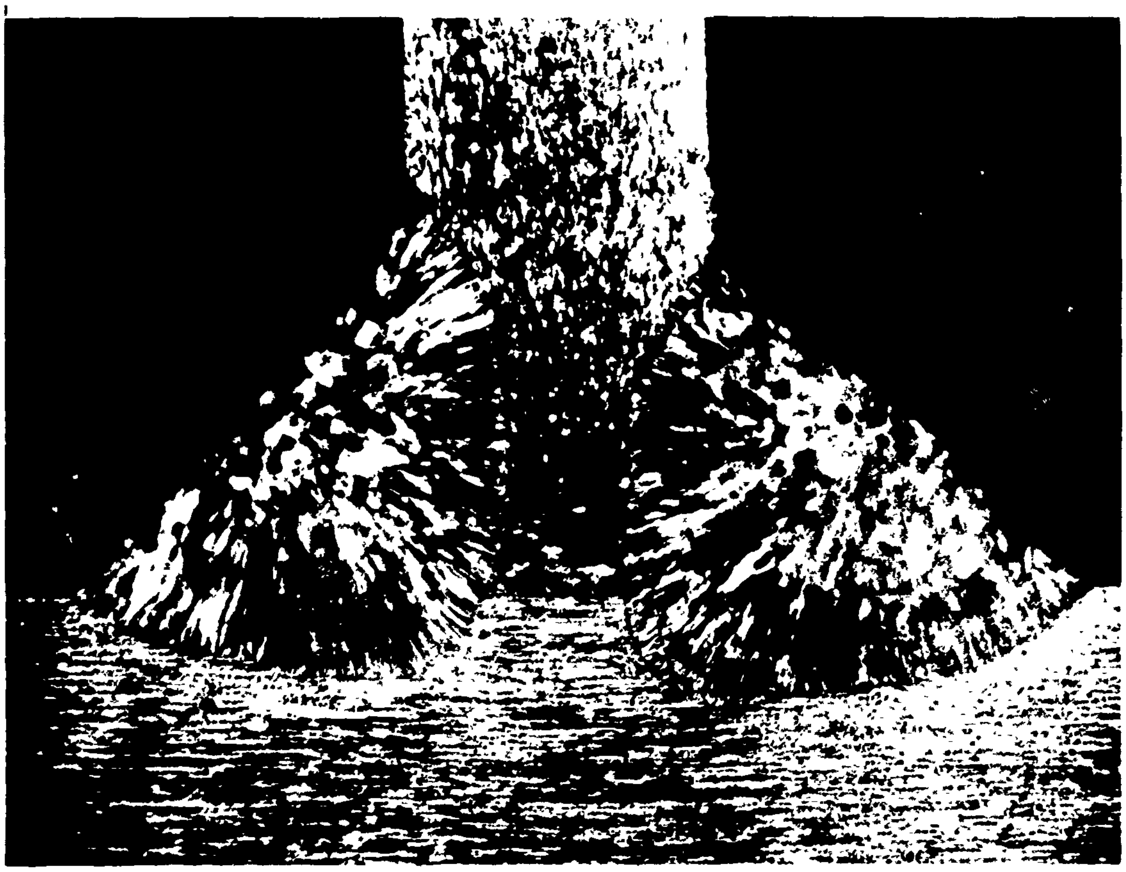


Fig. 4-20 - Macrographs of Fillet Welds, Pulsed GMAW (15X)

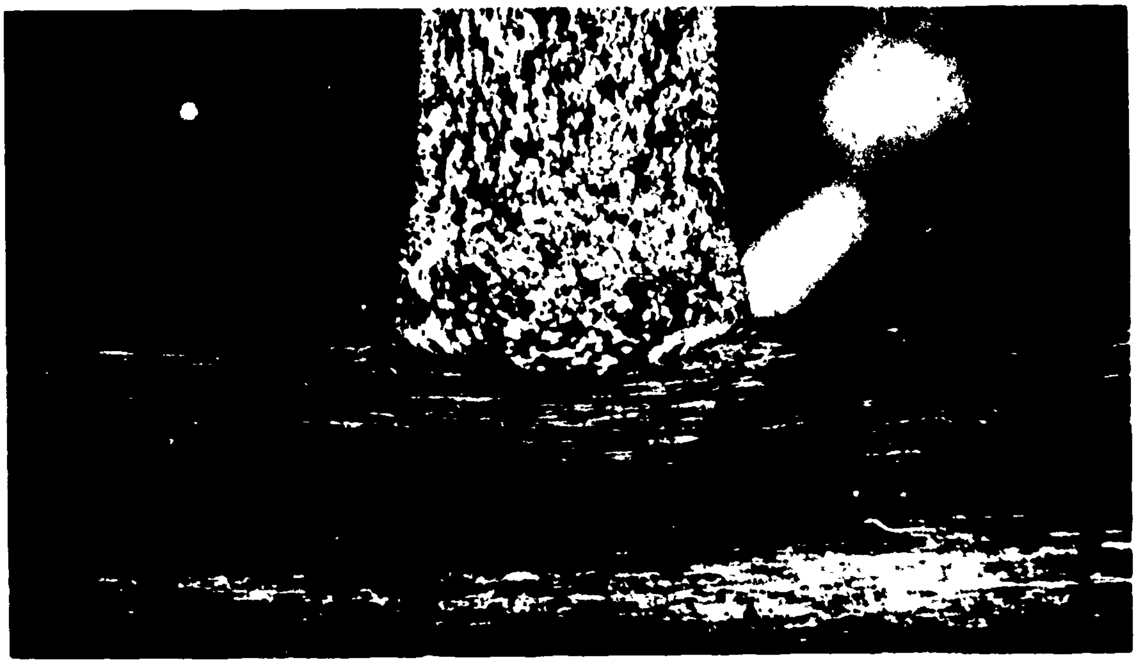


Fig. 4-21 - Macrograph of Joint, HF Resistance (15X)

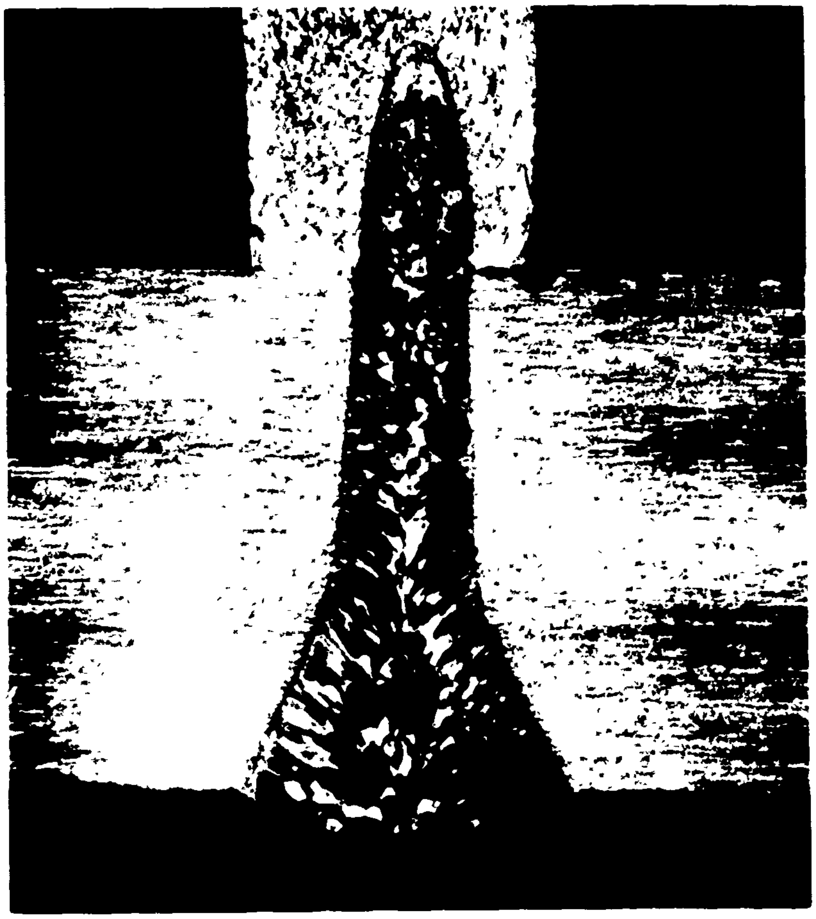


Fig. 4-22 - Macrograph of Weld, In Chamber Electron Be- Weldtrusion (15X)

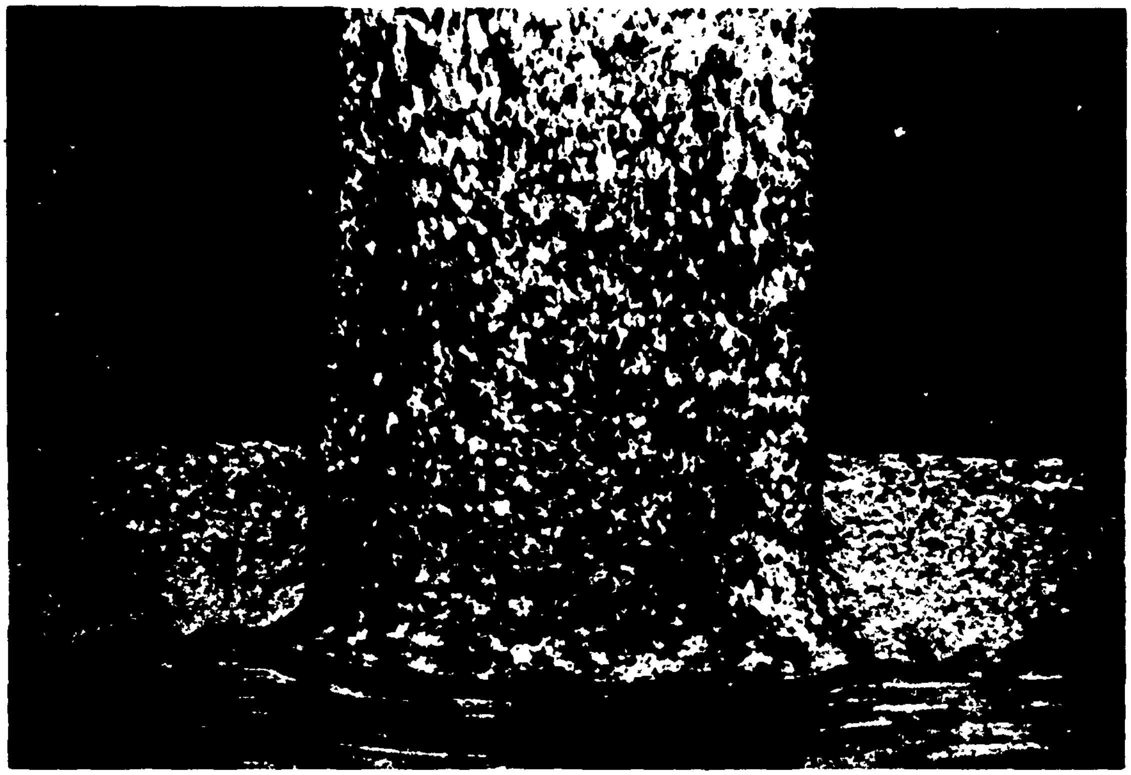


Fig 4-23 - Macrograph of Explosion Weld

Fig. 4-24 - Macrograph of Conventional GMAW Butt Weld
Made From One Side (8X)

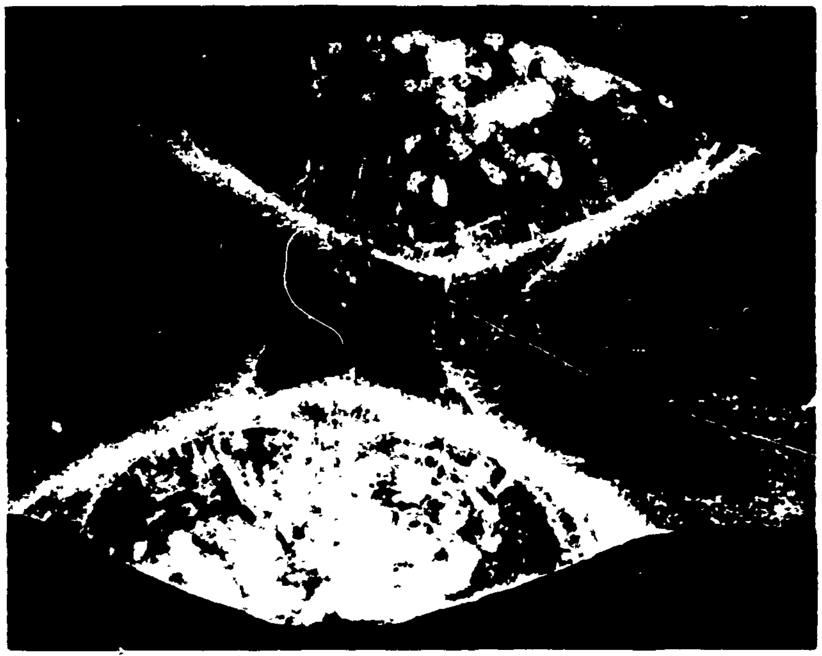


Fig. 4-25 - Macrograph of Conventional GMAW Butt Weld Made From Two Sides Without The Use of Back Chipping (10X)

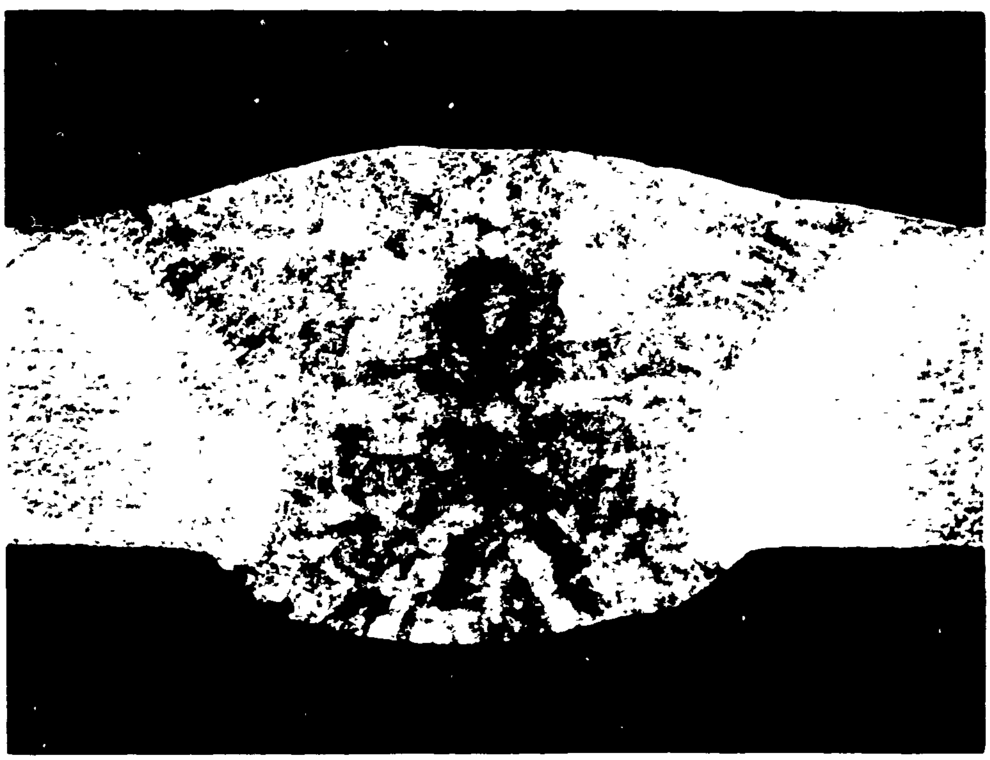


Fig. 4-26 - Macrograph of Plasma GMAW Butt Weld (8X)

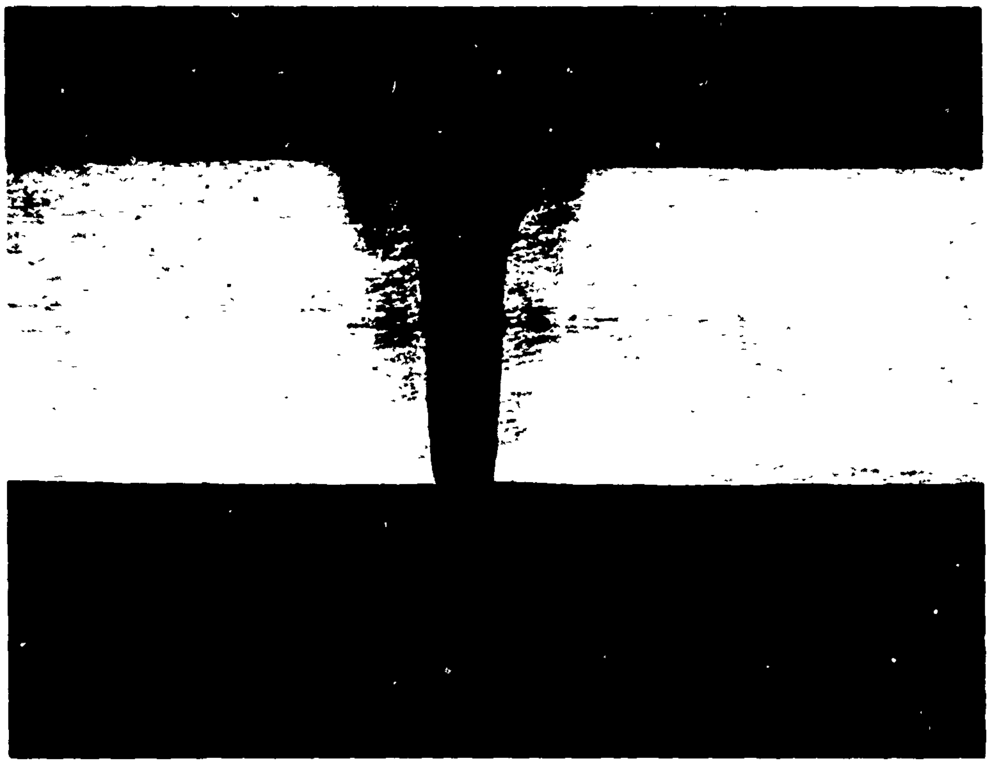


Fig. 4-27 - Macrograph of Sliding Seal Electron Beam Butt Weld (8X)

Section 5 - Analysis of Results

5.1 "T" Stiffened Panels

5.1.1 Welding

5.1.1.1 GMA Welding

5.1.1.1.1 Facilities and Equipment - It was determined in the initial screening test described in paragraph 2.1.1.6 that the constant energy power supply, otherwise known as the drooping volt ampere characteristic power supply, is the best power source for automatic GMA welding. The costs for this power supply are relatively low. Conventional GMAW equipment is readily available from several manufacturers. Conventional GMA welding has been used for approximately 30 years in shop fabrication and in very primitive field erection environments. Most power sources and wire feeders used for automatic GMA welding can be modified for field erection-type, semi-automatic GMA welding. This is of substantial advantage. For shop fabrication, curtains or shielding devices should be readily available for eye protection of other employees in the shop area. In addition, recirculating water for cooling of the larger GMAW equipment is also necessary. Because of its long years of utilization, GMAW equipment generally requires minimal maintenance.

5.1.1.1.2 Joint Design - The joint design was adequate for conventional GMA welding. It should be noted that the bottom of the web of the "T" should be kept as square as possible to minimize the amount of rocking of the "T", thereby reducing the tooling for in-shipyard fabricating, where distortion control is most critical.

5.1.1.1.3 Joint Preparation and Cleaning - Joint preparation and cleaning is minimal for GMA fillet welds. No edge profiling or beveling is necessary. The extruded stiffener was welded as received from the plant. Solvent wiping followed by wire brushing is the most typical type of cleaning done in shipyards utilizing GMAW for fillet welding aluminum today. For a large volume of construction, such as all-aluminum large ships, etching tanks have been utilized, more economically, to do volume cleaning of the sheet, plate and extrusion materials before welding. Even with etchant cleaning of the materials before cutting and erection, solvent wiping of the weld joint should be done immediately before welding to remove any oils or lubricants that were picked up during the sawing or erection precedures.

5.1.1.1.4 Operator Training - The welding operator has to be experienced and trained especially for GMA welding. Semi-automatic welding, which is used for in-shipyard fabrication and field erection, will require a great deal of on-the-job experience. Although this process may require the most amount of time for operator training, it should also be recognized that because of its long period of use, the number of trained operators available for GMA welding is substantially higher than for any of the newer welding processes tested.

5.1.1.1.5 Shop Fabrication of 8 Ft. x 40 Ft. Panels - Shop Fabrication of subassemblies (8 ft. x 40 ft.) could utilize an automatic dual torch GMAW setup to join the longitudinal stiffeners to the sheet. In this situation, the welding carriage would actually ride the "T" stiffener. For a one-station setup of dual torch GMAW equipment, it is our estimate that the equipment cost would be around $15,000. The cost for fixturing and tooling to provide for low-distortion construction would be estimated at about $20,000.

5.1.1.1.6 In-Shipyard Fabrication - For typical shipyard fabrication as is now practiced by the majority of the U.S. Shipyards for aluminum construction, the conventional GMAW process would be used for semi-automatic fillet welding and semi-automatic butt welding. Here the portability of GMAW equipment is very advantageous. Most semi-automatic welding used in shipyard fabrication utilizes a minimal amount of fixturing. The cost of the constant energy power supply, wire feed equipment, and welding torch for each operator would be approximately $6,000.

5.1.1.2 Pulsed GMAW

5.1.1.2.1 Facilities and Equipment - Pulsed GMA welding equipment, providing high-frequency modulation (2-25 K Hz) of direct current, is rather new on the market. The size and the costs of some of the pulsed power supplies can be substantially higher than those for GMAW equipment. In all other respects, however, pulsed GMAW equipment will require the same facilities as does conventional GMAW.

5.1.1.2.2 Joint Design - Same as 5.1.1.1.2

5.1.1.2.3 Joint Preparation and Cleaning - Same as 5.1.1.1.3 .

5.1.1.2.4 Operator Training - Same as 5.1.1.1.4

5.1.1.2.5 Shop Fabrication of 8 Ft. x 40 Ft. Panels - The initial capital expense of pulsed GMAW equipment is substantially higher than conventional GMAW apparatus. Although tooling and fixturing would be identical with conventional GMAW welding, the costs for the power supplies could be two to ten times ($3,000 to $40,000) the cost of good conventional GMAW power supplies depending upon pulse frequency and other optional features. Total investment cost for a dual torch automatic welding setup, similar to that described for conventional GMAW welding, would cost $18,000 to $92,000.

5.1.1.2.6 In-Shipyard Fabrication - The size of some pulsed GMAW power supplies would preclude them from being used in shipyard or field erection-type applications. The shear bulk of some of the power supplies could not be tolerated in moving equipment throughout the ship or around the shipyard. Total cost for a semi-automatic pulsed GMA welding setup, per individual welding operator, is estimated at $8,000 to $35,000.

5.1.1.3 High-Frequency Resistance Welding

5.1.1.3.1 Equipment and Facilities - Welding equipment, similar to the Battelle Laboratories unit used in this contract, is considered commercial, producing steel "I", "H", and "T" beams with in-line scarfing of the weld flash to achieve a uniform filleted weld between the flanges and the web of the beams. The addition of in-line scarfing both for steel and aluminum assures removal of any unwelded portion at the edges of the weld and results in a structural section with 100% fusion. Equipment and facilities for welding two stiffeners at a time to a sheet element has not been produced at this time. Such a facility, if produced, would be capable of finishing very flat panels at a very high-production rate. Welding of two stiffeners at a time could be accomplished at 100-300 ft. per minute.

5.1.1.3.2 Joint Design - The joint design for the "T" stiffened panels used in this contract resulted in uneven heating of the two pieces to be welded. This resulted in the need for an in-line heater. Better heat balance could be obtained if the "T" section could be redesigned. This would involve increasing the mass at the end of the web of the extrusion. Figure 5-1 shows a typical example where the last 3/8" of the web of the extrusion has been increased to a 1/4" thick. By adjusting the welding conditions established during this contract, the necessary heat balance can be obtained. By using in-line scarfing, the excess metal from the completed joint will be removed automatically to produce a sound, smooth fillet weld.

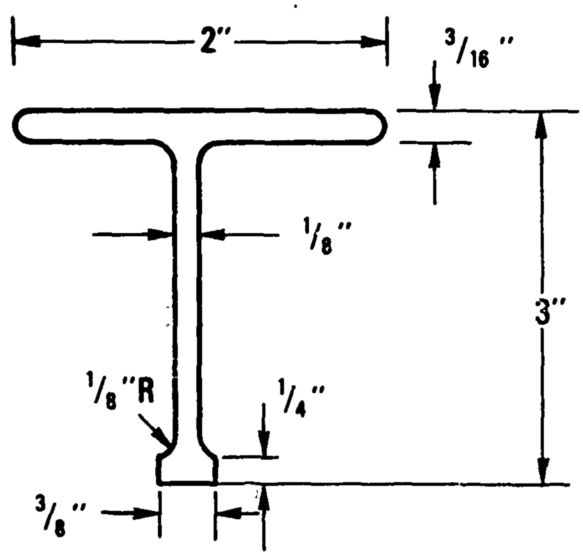


FIG. 5-1

Aside from these changes, the web of the extrusion does not have to be beveled or machined in order for high-quality, high-frequency resistance welding to take place. Material can be used as received from the extrusion plant.

5.1.1.3.3 Joint Preparation and Cleaning - No special cleaning or joint preparation need to be done over and above those described for conventional and pulsed GMAW welding.

5.1.1.3.4 Operator Training - The final dimensions of the finished panel will be determined by the equipment settings, however, the operator must be mechanically adept and knowledgeable in the operation of the equipment.

Semi-skilled and skilled mechanics have been found to be the best source for such operating personnel. Training for such personnel takes place during the initial equipment installation trials. Manual skill is not necessary.

5.1.1.3.5 Shop Fabrication of 8 Ft. x 40 Ft. Panels - With better joint design and heat balance, flat panels with minimal distortion can be produced on high-frequency resistance welding equipment. The equipment and facilities for producing two stiffeners at one time on a sheet element would probably cost about $800,000. With the high speed welding characteristic of this joining method, approximately six passes on a piece of equipment, designed for two stiffeners at a time, would be required to produce an 8 ft. x 40 ft. longitudinally stiffened panel. This would result in a total welding time of only about 6 minutes. Because of the nature of the equipment, fixture costs are included in the cost of the equipment.

5.1.1.3.6 In-Shipyard Fabrication - Because of the movement of the material through the welder and lack of portability for high-frequency resistance welding equipment, it is not applicable to shipyard or field erection-type fabrication.

5.1.1.4 Explosion Welding

5.1.1.4.1 Facilities and Equipment - The Battelle Columbus Laboratory's equipment used to make explosion welds in this contract could be used for production-type explosion welding. The facilities would be the major capital cost for explosion welding. These would include an area for cleaning and assembling the parts, an area for assembly of the explosive materials, and an adjacent explosive storing bunker. The actual explosion welding would take place within a close proximity of the supporting areas, in an underground vault or suitable concrete structure above ground, for containment of the explosion welding shock and noise. Such a facility would require an investment of several hundred thousand dollars, depending on the production rate required. It should be kept in mind that the cost of such a facility could also be justified on the basis that the facility would be able to explosion form complex curvature sheet or plate parts.

5.1.1.4.2 Joint Design - Most of the problems with explosion welding in this contract were due to the need for complex tooling to support the narrow web of the "T" stiffener during explosion welding. Aluminum explosion welding will be more economical, with lower-cost tooling, if a better sheet-to-web thickness ratio is used. It will probably be necessary for the web of the "T" stiffener to be thicker than the sheet material. In the case of 3/16" sheet, the web would probably have to be over 1/4" in order to be able to greatly reduce the amount of tooling used for explosion welding. This reduction in tooling would make explosion welding more attractive both technically and economically for thicker multi-stiffened panels.

5.1.1.4.3 Joint Preparation and Cleaning - All that is required for joint preparation and cleaning of explosion welded parts is a simple degreasing before assembly. Although it was not evaluated in this program, there may be some enhancement of quality and consistency of the weld if a mild, chemical cleaning is employed.

5.1.1.4.4 Operator Training - Explosion welding is a totally automatic process. Minimal training of the operator is required. The major requirement for the operator would be strict adherence to cleanliness during the assembly and to safe regulation to handling of the explosives. The handling and assembly of the SWP-1 explosive material can be done routinely, for the material is relatively safe compared to most explosives.

5.1.1.4.5 Shop Fabrication of 8 Ft. x 40 Ft. Panels - If explosion welding is to be used for fabrication of large aluminum stiffened panels, the thickness of the materials used will have to be increased. As described in paragraph 5.1.1.4.2, increased web thickness will be necessary in order that the web will not buckle during explosion welding. The explosion welding should be less difficult as the thickness of the web of the extrusion is increased; as the ratio of the web-to-sheet thickness increases; and as the ratio of the height to the thickness of the web of the extrusion decreases.

The contract demonstrated the technical feasibility to explosion weld alloy 5456 to produce a stiffened panel. The complexity of the tooling setup required to weld the thin gauge "T" stiffened panel used as a basis for this contract probably precludes the use of explosion welding for welding thin gauge panels in the future. Some of the experimentation also indicates the need for accurate fit-up of the tooling support system against the web of the "T". Without this accurate fit-up, a central section of the beam often times will not weld.

5.1.1.4.6 In-Shipyard Fabrication - Due to the complexities of controlling explosive materials in shipyards and attempting to control noise and the blast effects of an explosion, explosion welding cannot be considered for shipyard or field erection fabrication.

5.1.1.5 In-Chamber Electron Beam Weldtrusion -

5.1.1.5.1 Facilities and Equipment - Electron beam welding equipment is extremely expensive and because of the necessary vacuum chamber it is very large, bulky and not portable. The equipment used by Babcock and Wilcox possessed a chamber 68" x 68" x 72" and cost approximately $300,000. It is important that electron beam welders be provided with proper electrical power and with the required venting systems to achieve the proper vacuum conditions necessary for welding.

5.1.1.5.2 Joint Design - The joint design used in this contract was not adequate. A new joint design to widen the bottom of the leg of the "T" extrusion would permit a wider electron beam weldtrusion (See Figure 5-1). This would give a wider cross-sectional area of weld and, hopefully, produce higher mechanical properties and improved stiffened panel performance.

5.1.1.5.3 Joint Preparation and Cleaning - Joint fit-up is very critical in electron beam welding since filler wire is not used. Joint fit-up usually has to be held to within .005". Cleaning is also very important, and all materials are chemically cleaned prior to welding. If a contaminant is present during welding, porosity or arcing of the beam may occur.

5.1.1.5.4 Operator Training - Operator training is minimal as electron beam welding is an automatic operation. Once the beam is set up and aligned by the operator, welding control is automatic. At most electron beam facilities, however, the operator is also required to repair and maintain his unit. This requires a good deal of training and experience.

5.1.1.5.5 Shop Fabrication of 8 Ft. x 40 Ft. Panels - Welding of the "T" extrusion to sheet could be done with this process at a very high welding speed. In order to weld longitudinally stiffened aluminum panels of this size, a large vacuum chamber would have to be built. It might be more cost effective if a soft vacuum or out-of-vacuum electron beam welder could be utilized. The cost of a panel-type construction facility with a large vacuum chamber would cost approximately 1-1/2 million dollars. Additional tooling and fixturing for an 8 ft. x 40 ft. panel would be about $20,000.

5.1.1.5.6 In-Shipyard Fabrication - Because of the high cost and the lack of portability of equipment, in-chamber electron beam weldtrusion is not applicable to shipyard or field erection-type fabrication.

5.1.2 Evaluation

5.1.2.1 Distortion and Shrinkage - Table 5-1 summarizes average distortion and shrinkage values measured for the stiffened panels. Sketches showing the bow measured as well as the angular distortion measured were presented in Table 4-1. The negative value of change in length of sheet indicates that the sheet was shortened by the joining process. The change in width of the sheet was not measured in every case and was small in those cases measured (see Tables 4-1 and 4-2) and thus is not presented here. Likewise, the change in length of the extrusion was also relatively small compared to the change in length of the sheet (see Table 4-1 and 4-2) and also was not measured for panels of each process.

The bow introduced varied considerably with joining process. The minimum bow occurred for panels made by the conventional GMAW process which were pre-distorted. The largest bows occurred for the HF resistance welded and the explosion welded panels. It appears that the amount of bow primarily was a function of the technique and procedures used to make the panels, such as pre-distortion and fixturing, rather than welding variables such as heat input. For example, the panels made by the in-chamber electron beam weldtrusion process had a slightly greater bow than did panels made by either conventional or pulsed GMAW even though the heat input for the electron beam welds (2,508 joules/in) was less than 1/2 that for the panels made by conventional GMAW (5,415 joules/in) (See Section 2). The small change in length of the sheet for the electron beam welded panels relative to those made by GMAW processes perhaps does reflect the effects of heat input. There was no obvious correlation between shrinkage occurring in the panel and bow in the panel. In the case of panels made by the conventional GMAW process, for example, pre-distortion produced a small bow in the panel but did not appear to affect the shrinkage. The average angular distortion of the sheet appears to be primarily a function of the weld process and procedure although in this case the low angular distortion in the panels made by the electron beam process suggests that heat input also contributes to angular distortion. The amount of twist was relatively small for all panels.

5.1.2.2 Residual Stress - Residual stresses at selected locations in the stiffened panels are presented in Table 5-2. These measurements show that large tensile stresses occurred near the weld for panels made by the conventional and pulsed GMAW compared to those for electron beam welding, reflecting the relative heat input of these processes, and the size of the area of melted metal. The distribution of residual stresses in the high frequency resistance and explosion welding processes were quite different than those in the GMAW processes probably as a result of the procedures used to make the panels. The magnitude and distribution of residual stress does not appear to be related to the amount of bow in the panels. Panels made by the conventional GMAW process with pre-distortion had residual stresses comparable to that for the pulsed GMAW specimens even though the amount of bow is considerably different in the two cases. Shrinkage values perhaps are related to the general level of residual stress in the sheet.

5.1.2.3 Hardness - Hardness determinations were used as an indication of the extent of heat affected material at the joint. There was no large decrease in hardness in the sheet near the welds for conventional and pulsed GMAW and high frequency resistance welding. Some decrease in hardness over about a 1/2 inch length was present in the sheet for the panels made by the electron beam welding process. The panels made by the explosion welding process showed an increase in hardness of both the sheet and the extrusion in the region of the joint. Thus, in all processes the amount of material affected by the joining process was low. Thus, little effect of heat affected material was expected in the static bending tests.

5.1.2.4 Corrosion - The results of the ASSET exfoliation tests indicated that excellent resistance to exfoliation was maintained in the as-welded condition with all of the welding processes. There was some indication of mild exfoliation of the stem of the 5456-H111 extrusion and it appeared to be greater with the high frequency resistance weldments than with the other processes probably because of the preheat. Exfoliation has been observed previously on 5456-H111 extrusion when heated one week at 212°F and exposed to ASSET, so that this is not unusual. Service experience of many years is showing no evidence of exfoliation of 5456-H111 extrusion used in boat hull construction.

Stressed beam assemblies for the various weld processes have been exposed to the 3-1/2 per cent NaCl alternate immersion tests for 74 and 114 days, without showing any evidence of stress corrosion cracking. Both periods of exposure are of sufficient duration to indicate that none of the weld processes under evaluation had a highly detrimental effect upon the resistance to SCC, even when heated one week at 212°F to simulate the effects of long time natural aging and exposed to this particularly aggressive environment. These periods of exposure, however, are not of sufficient duration to indicate conclusively that the various welding processes produced no detrimental effect upon the resistance to SCC. It is planned to continue the exposure of these stresses beam assemblies beyond the completion of the contract.

5.1.2.5 Static and Fatigue Tests - Table 5-3 presents calculated static strengths for panels, based upon the base metal properties of the sheet and extrusion. Tensile stresses at failure approximately equal to base metal tensile strengths of the sheet were developed. This was expected because the heat affected zones in panels from all welding processes were small as determined by hardness determinations. In two of the processes, electron beam and explosion, the joint between the stiffener and the sheet failed during test. The electron beam weld was only about 0.050-in. wide (see Figure 4-22) and a shearing failure occurred in the weld during the tests. Failure at the interface between the stiffener and the sheet also occurred in static tests of the panels made by the explosion method, apparently a result of inadequate bond obtained between parts. The bending tests showed that with adequate shear capacity at the interface of the extrusion and the sheet, the strength of the part could be based upon base metal properties for the processes and proportions considered.

There was overlap in the fatigue lives of stiffened panel specimens subjected to 15 ksi maximum stress in air and in seawater, but the life in air was about double that in seawater. Greater differences in lives would be expected at lower stresses. For example, at the 10 ksi stress level used for most of the tests in seawater, failure would not have been expected if the tests had been made in air. The fatigue fracture surfaces in two of the stiffened panels are pictured in Figures 5-2 (explosion welding) and 5-3 (high frequency welding). Failure origins for other panels are shown in electron microscope fractographs in Figures 5-4 to 5-6. Internal gas pores, 0.1 in. long (Figure 5-4) which formed at the edge of the weld served as failure origins for two of the panels tested in air. Most of the other fatigue failures initiated at discontinuities at the weld surface. Although the panels tested in seawater generally had lower fatigue strengths than those tested in air, only Specimen E-11-5-4 had an origin in a corroded region (Figure 5-5).

It is not possible to relate residual stresses to fatigue behavior in this investigation. Large tensile residual stresses occurred near the weld for panels made by the conventional and pulsed GMAW. Since the fatigue strengths for these panels were about the same or higher than those for the other processes, it appears that joint configuration and roughness, or imperfections in the joint, were the controlling factors in fatigue strength.

5.1.2.6 Metallographic Examination - Metallographic examinations of the conventional GMA welds showed that they were of good quality although some internal gas voids were present in all three specimens checked. The grain structure was good and there was no evidence of sheet cracking. Similar comments apply to the pulsed GMAW and the electron beam welds. In the case of the electron beam welds there was some solidification cracking at the weld tip. The high frequency resistance welds showed good grain structure. There was evidence of an unfused zone at the edge of the interface ranging from .0090-in. to .0270-in. on both sides of the joint. For the explosion welded panels metallographic examination indicated an unfused zone of 0.01350 in. and 0.00675 in. on one edge of each of the two specimens examined. Two specimens taken near the end of an explosion joined stiffened panel failed during preparation of the sample; therefore, metallographic examinations were not completed on these parts.

5.2.0 Butt Welds

5.2.1 Welding

5.2.1.1 GMA Welding

5.2.1.1.1 Facilities and Equipment - The facilities and equipment necessary for automatic and semi-automatic GMA butt welding are the same as those for GMA fillet welding. This is discussed in paragraph 5.1.1.1.1.

5.2.1.1.2 Joint Design - The joint design for butt welding of 3/16" sheet is not critical. No edge bevel is necessary. For the contract, saw-cut parts were welded together. The straightness of the saw cut will affect the amount of distortion caused by the butt welding of 3/16" sheet.

5.2.1.1.3 Joint Preparation and Cleaning - The cleaning procedure described in paragraph 5.1.1.1.3 for conventional GMA fillet welding are adequate for GMA butt welding.

5.2.1.1.4 Operator Training - See paragraph 5.1.1.1.4.

5.2.1.1.5 In-Shipyard Fabrication - Automatic and semi-automatic GMAW are very versatile and can be used to weld thicknesses of 1/16" to 10". Butt welding of sub-assembled panels and large sub-assembly modules can be done automatically with this process. Semi-automatic butt welds can be made with the proper operator experience.

5.2.1.2 Plasma GMA Welding

5.2.1.2.1 Facilities and Equipment - Only one piece of plasma GMAW process equipment has been developed. This piece of equipment, located in the Netherlands, has been solely used in the laboratory. Phillips has given Alcoa an estimate of $28,300 for a complete plasma GMAW butt welding equipment set-up.

5.2.1.2.2 Joint Design - See paragraph 5.2.1.1.2

5.2.1.2.3 Joint Preparation and Cleaning - See paragraph 5.2.1.1.3

5.2.1.2.4 Operator Training - See paragraph 5.2.1.1.4

5.2.1.2.5 In-Shipyard Fabrication - See paragraph 5.2.1.1.5

5.2.1.3 Sliding Seal Electron Beam Welding

5.2.1.3.1 Facilities and Equipment - Presently, there are two pieces of equipment capable of producing a sliding seal electron beam weld. One piece of equipment is in France and the other piece at Grumman Aerospace Corporation, Bethpage, New York. Both pieces of equipment were manufactured by Sciaky. Sciaky has mentioned that a similar piece of equipment would be approximately $400,000. A facility utilizing sliding seal electron beam equipment would have to be designed so that large amounts of electrical power could be available from various positions in the shop and that the sliding seal EB welder could be moved about the shop, around various sub-assemblies, modules and possibly the ship construction itself.

5.2.1.3.2 Joint Design - The joint fit-up for electron beam but welding is very critical. Machined edges are necessary with fit-up required to within .010" to .020" thousandths of an inch. This is necessary because no filler wire is used in sliding seal electron beam butt welding.

5.2.1.3.3 Joint Preparation and Cleaning - See paragraph 5.1.1.5.3

5.2.1.3.4 Operator Training - See paragraph 5.1.1.5.4

5.2.1.3.5 In-Shipyard Fabrication - The sliding seal electron beam welder is movable, through the use of a small crane, and can be used for shipyard construction. Butt welds can be made if the sealing apparatus shoe can fit between the stiffeners already assembled on the panels or sub-assemblies. Only automatic welds can be made with the sliding seal EB welder. Methods for backing up the weld by the use of aluminum backing strips or back-up tape must be developed.

5.2.2 Evaluation

5.2.2.1 Distortion and Shrinkage - The results for the out-of-plane distortion of butt welded panels (Table 4-6) shows the greatest longitudinal bow for the conventional GMAW process and the least bow with the electron beam welds. Because the panels had quite different lengths, however, the values of bow should not be compared directly. If all panels were assumed to have a circular curvature, the radius of curvature can be used to compare panels. The approximate radius of curvature, R, is given by the following:

$$R = \frac{L^2}{8b} + b/2$$

where R = the radius of the circle, in.
L = length of panel, in.
b = measured bow at midspan, in.

The radius of bow for the conventional GMA welds using this formula is about 450 inches whereas the radius of curvature for the plasma GMAW panels is about 330 inches. Thus, the bow in the panels welded by plasma GMAW was slightly greater than that for the panels made by conventional GMAW panels. The bow for panels made by the electron beam process were less than 1/5 those of conventional GMAW. The transverse bow in the panels made by the electron beam welding process was less than 1/2 that for panels made by conventional or plasma GMAW. In this case, heat input during welding apparently was a major factor since the GMAW and plasma butt welds had heat inputs of about 11,000 and 13,000 joules per inch, respectively, whereas the electron beam welds had a heat input of about 3,000 joules per inch. The shrinkage in the electron beam welds also was considerably less than that for the conventional GMA welded panels also reflecting relatively less heat input. The weld beads for conventional and plasma GMAW were much larger and more triangular shaped than the EB welds. This is also detrimental to shrinkage and out-of-plane distortion.

5.2.2.2 Residual Stress - The patterns of residual stress in the panels made by conventional GMAW and plasma GMAW were similar in shape and the stresses were similar in magnitude. Those in the panel made by the sliding seal electron beam process were generally much lower than the other processes with the exception of a narrow region near the weld, in which the magnitude of the stress was similar to that in the other processes. The low heat of welding for the electron beam welds compared with those for the other processes apparently accounts for the difference in residual stress patterns in the specimens.

5.2.2.3 Hardness - The hardness distributions in the butt welded panels also reflect the relative heat input of these processes. Both the conventional GMAW and the plasma GMAW panels had wider heat affected zones than did panels made by the electron beam process.

5.2.2.4 Corrosion - The butt-welded specimens heated one week at 212°F showed some severe local attack along the outer edge of the heat affected zone which in the beginning stage has the appearance of exfoliation. This was evident with all of the welding procedures for both butt and fillet weldments. It is not cause for great concern as this is a very aggressive test environment to which the welds were subjected. It does indicate that with long time natural aging or exposure to slightly elevated temperatures for a brief period of time, precipitation may occur to the extent that some local attack can be anticipated if subjected to an aggressive environment. However, experience has shown that this alloy and temper provide excellent service for ship structures.

The butt welded panels are not showing any evidence of stress corrosion cracking. As in the case of fillet welded panels, these specimens will remain in test until a one-year exposure is completed, unless SCC occurs or space is needed to expose other contract specimens. Subsequently, the results will be reported by letter.

5.2.2.5 Static and Fatigue Tests - Table 5-4 summarizes static tests of butt welded panels and relates strength to base metal properties. The panel made by the electron beam process exhibited tensile and yield strengths comparable to that of the base metal. The strength properties of panels made by the other two processes were also good but generally slightly lower than the original base metal properties. Elongations as measured over a 10-in. gauge length ranged from a low of 6.3% for the conventional GMAW panels to 9% for the electron beam welded panels. Failure occurred adjacent to the weld bead except in the case of the electron beam panels in which case failure extended through the welds.

The fatigue strength of butt welds tested in air has been regarded to be a function of the acuity of the angle the weld bead reinforcement makes with the parent plate. As shown in Figure 4-24, this angle was greater than 90° for the root weld bead of the conventional GMA welds; the fatigue origins were at this location. Failures of the joints made by plasma GMAW also initiated at relatively steep weld beads on the root side. The weld bead acuity at the failure origins ranged from 52° to 59°. Electron beam welds did not completely fill the groove on the backside and, as shown in Figure 5-7, the fatigue failures initiated at roughness in such areas. For the tests in air this incomplete filling apparently provided no more of a stress concentration than the steep root weld beads of the GMA welds. For a maximum stress of 15 ksi, the fatigue lives of the conventional GMA welds were halved by testing them in seawater. Electron beam welds had shorter lives in seawater than the plasma GMA welds even though, as illustrated in Figure 5-8 for an electron beam weld, there was no evidence of corrosive attack at the failure origins of any of the butt welds.

5.2.2.6 Metallographic Examinations - Metallographic examinations showed that welds of all processes were of excellent quality. No cracks or excessive amounts of porosity were present in any of the joints.

TABLE 5-1

DISTORTION SHRINKAGE IN STIFFENED PANELS

Weld Process	Average Bow 4 ft. Panel, in.	Average Change in Length of Sheet in 47-1/2 in., in.	Average Angular Distortion of Sheet at Midspan, θ	Average Twist in 4 ft Panel, Degrees and Minutes
Conventional GMAW Predistorted (12 spec)	0.011	-.044	89°-32'	0°29'
Without predistortion (2 spec)	0.051	-.058	88°-25	0°44'
Pulsed GMAW (12 spec)	0.082	-.054	88°-9'	0°52'
In Chamber - Electron Beam Welding (7 spec)	0.091	-.013	90°-8'	0°29'
HF Resistance Welding (1 spec)	0.277(a)	+0.02(b)	89°-16'	0°26'(a)
Explosion Welding (4 spec)	0.279(a)	--	91°-8	0°16'(a)

(a) 3-ft. long panels.

(b) Based upon 3 measurements of panel made with preheat. Gage length was 24 in. The average change in length for 5 measurements for panel made without preheat was 0.00.

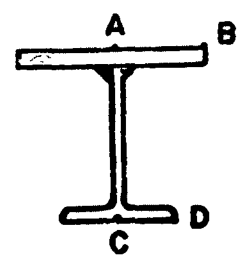
TABLE 5-2

RESIDUAL STRESS DETERMINATIONS

Weld Type	Stresses, ksi (a): Maximum Stresses in Plate: Location A	Location B	Maximum Stress in Extrusion: Location C	Location D
Conventional GMAW	+29.4	-7.2	-1.0	-8.2
Pulsed GMAW	+31.9	-7.2	+0.5	+3.1
In Chamber-Electron Beam Welding	+14.4	-14.4	+1.0	+6.2
HF Resistance	0	+12.4	+25.8	+6.2
Explosion Welding	+5.2	-13.4	-0.5	+5.2

(a) Location of measurements; stresses are maximum values measured on surface, not average values.

Note: Measurements taken with Berry Strain Gage (Mechanical).



LOCATION OF MEASUREMENTS

TABLE 5-3

CALCULATED STRENGTHS OF STIFFENED PANELS(a)

Process	(1) Calculated failure Stress, ksi(b)	(2) Apparent Maximum Interest Stress at Failure, ksi	(3) Shape Factor (2)/(1)	(4) Calculated Yield Strength, ksi	(5) Yield Str. From Test, ksi	(6) Shape Factor (5)/(4)
Conventional GMAW	53.3	54.4	1.02	37.3	38.3	1.03
Pulsed GMAW	52.8	54.0	1.02	37.1	37.8	1.02
HF Resistance	52.6	54.5	1.04	35.1	35.8	1.02

(a) Based on base metal properties (Table 4-9).

(b) Weighted average stress:

$$\sigma_f = \sigma_s = \frac{A_w}{A}(\sigma_s - \sigma_w)$$

σ_f = failure (or yield stress.

σ_s = tensile or yield strength of sheet.

σ_w = tensile or yield strengths of extrusion web.

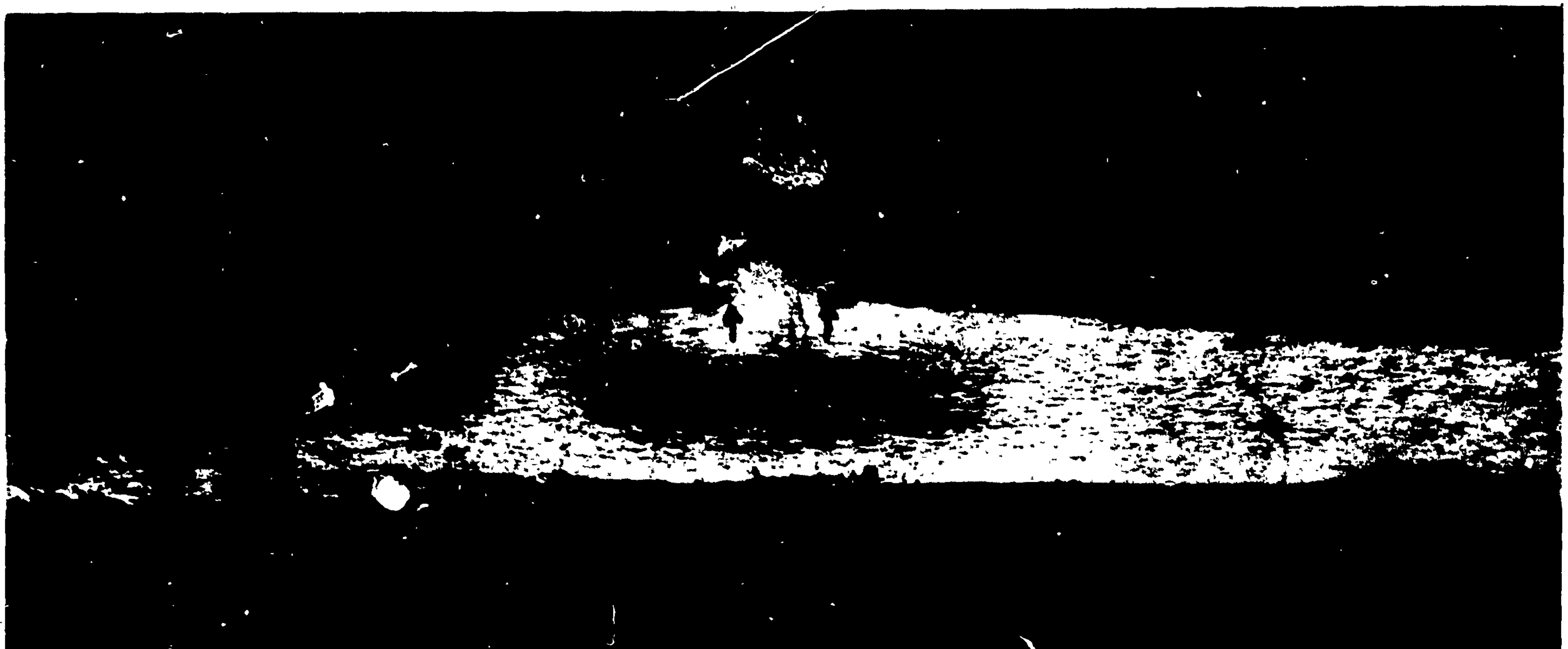
A = area of tensile flange; portion of section further than 2/3 c from neutral axis where c is distance from neutral axis to extreme fiber.

A_w = area of web only further than 2/3c from neutral axis.

TABLE 5-4

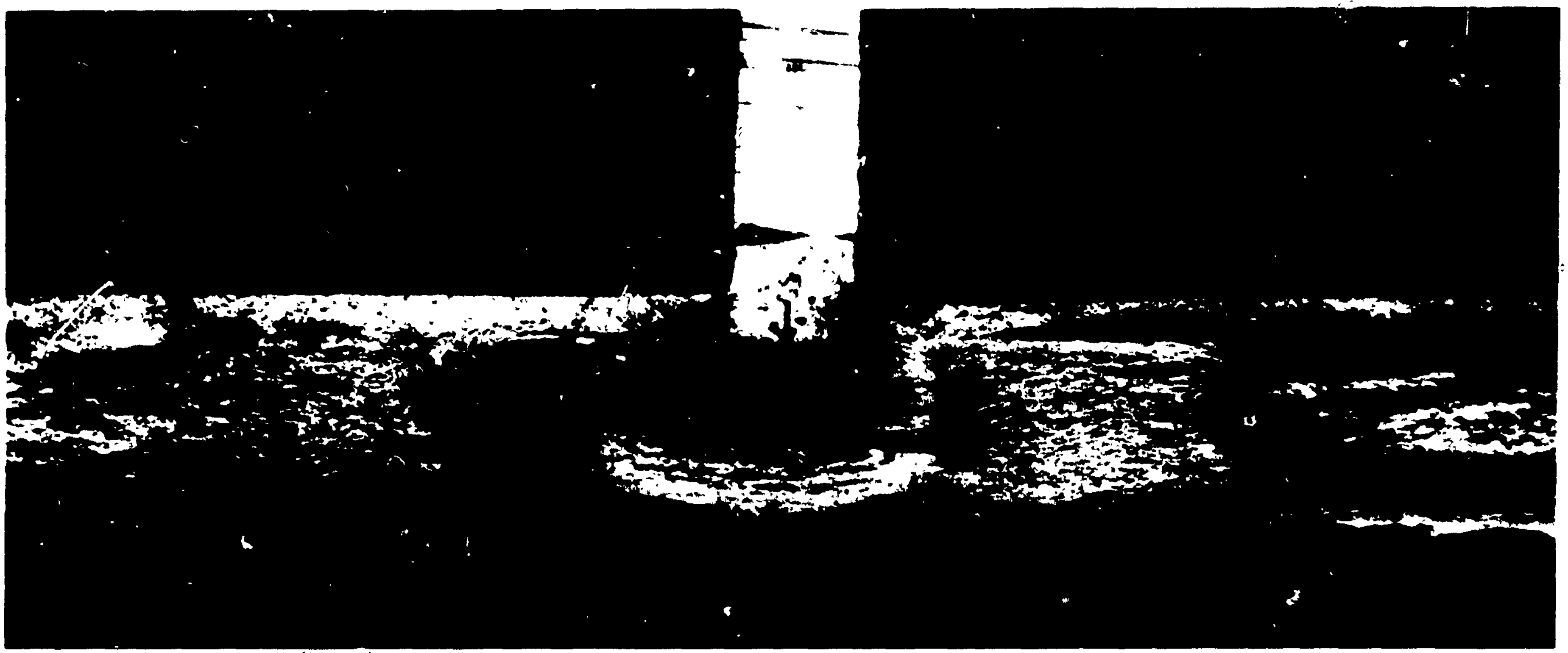
STATIC TESTS OF BUTT-WELDED PANELS

(1) Process	(2) Tensile Strength, ksi	(3) Ratio $\frac{(2)}{\text{Base Metal Strength}}$	(4) Yield Strength, ksi	(5) Ratio $\frac{(4)}{\text{Base Metal Yield Strength}}$	Elongation in 10 in., %	(7) Ratio $\frac{(6)}{\text{Base Metal Elongation}}$
Conventional GMAW	50.8	0.98	33.7	0.97	6.3	0.37
Plasma GMAW	53.0	1.01	32.4	0.90	8.3	0.52
Sliding Seal Electron Beam	54.5	1.04	35.8	1.02	9.0	0.55



11-12-11-1 6X

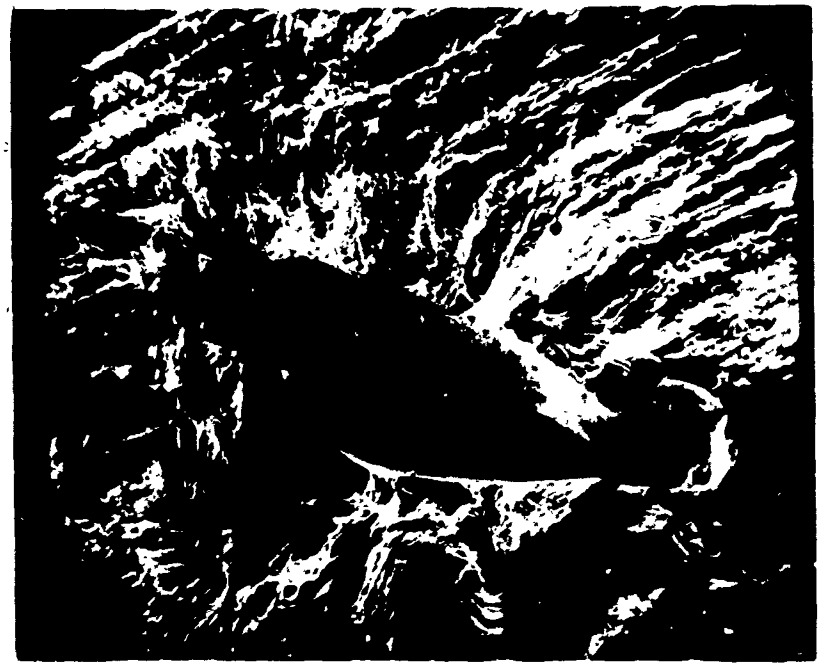
Fig. 5-2 Fatigue Fracture Surface of HF Resistance Welded Stiffened Panel Tested in Sea Water



N-3-19-3

6X

Fig. 5-3 Fatigue Fracture Surface of Explosion Welded Stiffened Panel Tested in Sea Water



4-12-11-1 30X

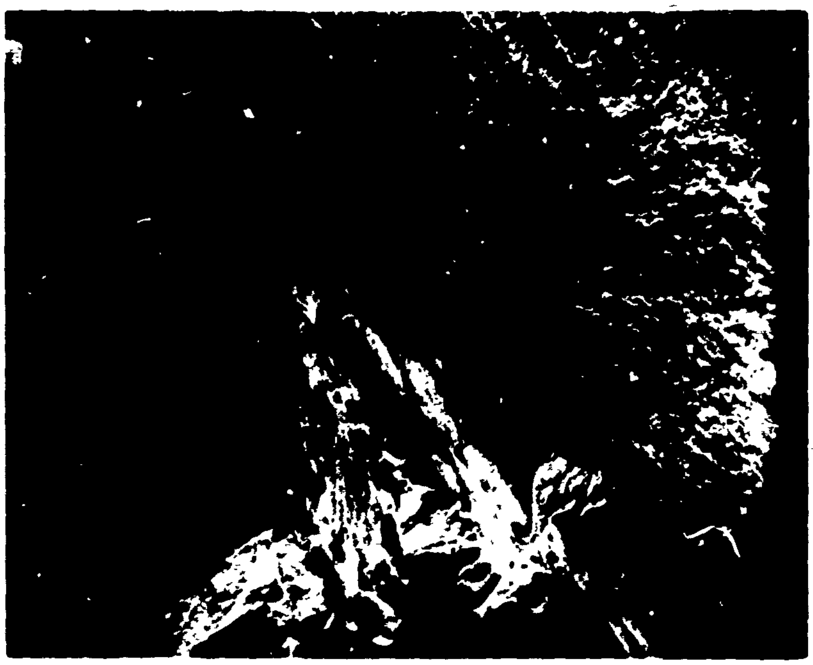
Fig. 5-4 Origin of Fatigue Fracture of Stiffened Panel at Gas Pore at Edge of Fusion of GMAW Weld. Test in Air.

E-11-5-4 Pulsed GMAW 100X

Fig. 5-5 Corroded Area Serving as Fatigue Origin For Stiffened Panels Tested in Sea Water

A-11-22-3 50X

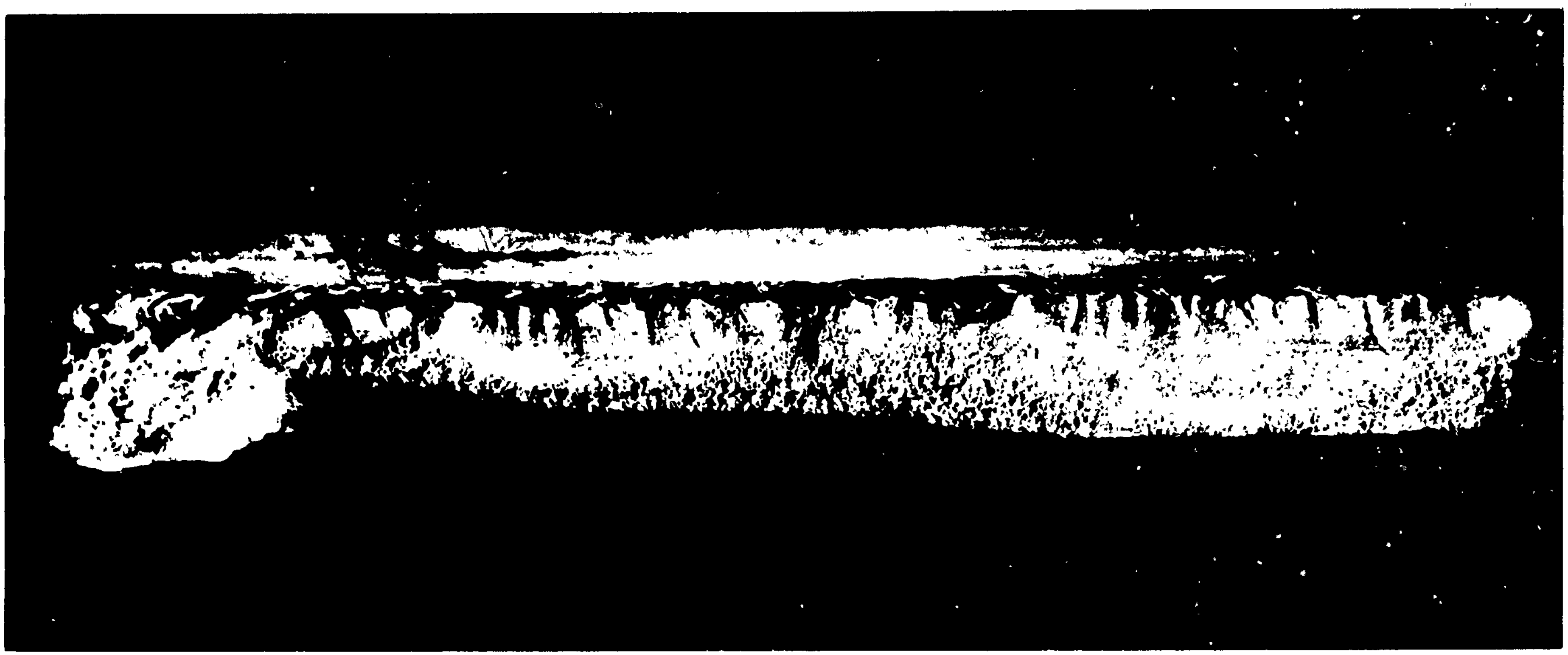
Conventional GMAW Weld a Failure Origin at Toe of Weld



J-12-11-3 20X

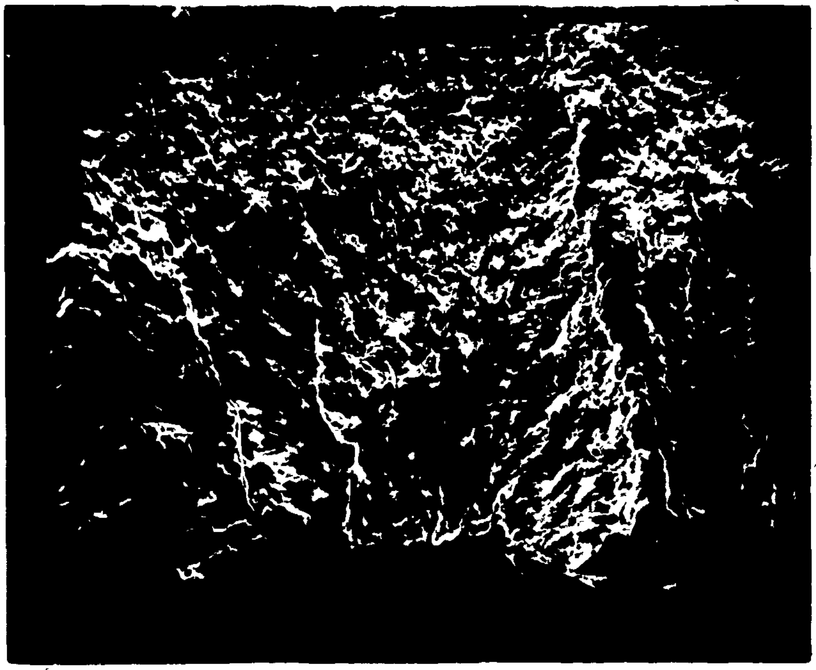
HF Resistance Weld Origin at Edge of Weld Flush

Fig. 5-6 Origins of Fatigue Failures of Stiffened Panels Tested in Sea Water



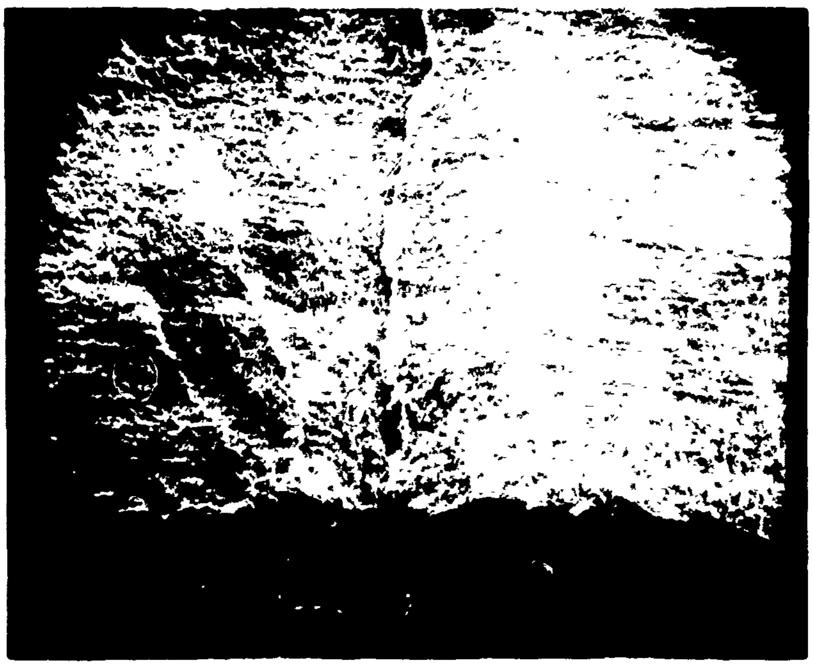
1A-6 5X

Fig. 5-7 Multiple Fatigue Origins of Electron Beam Butt Weld



1A-6 50X

Test in Air, 224,800 Cycles to 15.0 ksi



1A-3 30X

Test in Sea Water, 225,000 Cycles to 10.0 ksi

Fig. 5-8 Origins of Fatigue Failures of Electron Beam Butt Welded Specimens

Section 6 - Conclusions

6.1 General - To determine the optimum weld process for shipyard construction, Alcoa felt it was necessary to rank all of the processes against each other. Table 6-1 shows this ranking. It was decided to rate these joining processes against 14 different performance categories. The first six categories involve costs and economics. In order that the rankings would project real-life decisions, it was necessary for Alcoa engineers to add weight factors so that the most important categories could significantly affect the outcome of the rankings. The weight factors represent Alcoa's opinion as to the importance of each category. It is hoped that this comparison can be modified by other organizations attempting to decide on welding equipment, so that it will represent their feelings as to the importance of these categories. The ratings for the economic categories show our best approximations, based on information generated by Alcoa or supplied by our subcontractors. For the six economic categories, the highest number rating represents the process that would require the least cost. For the areas involving weld strength and soundness, distortion, and corrosion; the highest numbers represent the best performance versus all the other processes. It should be recognized by the reader that the ratings given each process by Alcoa engineers are based on the actual performance of the process during the fabrication phase of this contract. As with all ranking systems, this one required a good deal of judgment and compromise; however, Alcoa feels that Table 6-1 is a good representation of the overall performance and economics of the weld processes listed.

It was determined in Section 5 that only GMAW and pulsed GMAW equipment is applicable for in-shipyard fillet weld fabrication. The only major difference between GMAW and pulsed GMAW is the higher cost for the pulsed GMAW power supply equipment. The conventional GMAW process is considered superior to the pulsed GMAW for in-shipyard fabrication fillet welds. Therefore, a ranking for in-shipyard fillet welding is not included in Table 6-1. In attempting to analyze butt welding processes for use in panel shop fabrication, Alcoa was unable to determine areas where rating or the evaluation category would change from the ratings given the butt weld processes for in-shipyard fabrication. Therefore, shop fabrication butt welding rankings are the same as the in-shipyard fabrication butt weld rankings listed in Table 6-1.

The results of this ranking show that conventional GMA welding, based on the constant energy power source with a 50-50% Ar-He shielding gas mixture, is the most economic process that provides good welded joint parameters for all types of welding considered in this contract. Automatic GMA welding is superior in shop fabrication fillet welding, butt welding, and in-shipyard fabrication butt welding. Semi-automatic GMA welding is superior for in-shipyard fabrication fillet welding. It must be recognized that several of the processes evaluated during the contract showed good potential for increasing the economic effectiveness and/or individual weld joint characteristics, but the development of these processes has not reached a high enough level to overcome the basic soundness of GMA welding.

Based on the performance of all the welding processes tested in this contract, several general conclusions can be made about the performance of all of the welding processes used on 5456 sheet and extrusions.

In the area of corrosion, none of the welding processes, whether fillet welding or butt welding, resulted in any significant decrease in resistance to exfoliation or stress corrosion cracking in either the as-welded or the heated conditions. This demonstrates that the various heat inputs utilized by the weld processes tested were not high or of sufficient duration to effect the corrosion resistance of 5456 sheet and plate.

The attempt to determine the extent of fillet penetration by ultrasonic techniques was only partially successful. Ultrasonic techniques, using equipment that exist today, can determine the extent of penetration in a range of values only. The program detailed in the Appendix was not capable of precisely determining when the corner of a "T" fillet weld had been completely tied in with the sheet.

The laboratory work in this contract demonstrated that longitudinal and transverse predistortion can be employed to produce flat panels.

6.2 "T" Stiffened Panels - The weld joint evaluation program for stiffened panels showed that the fatigue strength of the "T" stiffened panels tested in sea water with a 15 ksi maximum stress had a log mean life of approximately one half that attained in the corresponding fatigue tests in air.

6.2.1 GMAW - In almost all areas of comparison including economics, weld soundness, and weld joint performance, conventional GMAW (constant energy power supply) was equal to or superior to the other fillet welding processes tested under this contract. The superiority of the GMAW weld process is shown graphically in Table 6-1. The GMA welding trials, which were conducted with three power sources (CE, CV, and CC), demonstrated the clear superiority of the constant energy (drooping volt-ampere) characteristic power supply. In addition, gas mixture studies on conventional GMA welding showed that the optimum gas mixture for good penetration, cleaning and weld soundness was a 50-50% mixture of argon and helium. A 1/8" size fillet weld with proper penetration can be developed using GMAW power supplies when high-heat input and high-travel speeds are employed. The 80 ipm travel speed with the use of 3/64" diameter electrode produced a consistent 1/8" fillet weld with very good joint strength. Additional studies on GMA welding showed that the slow run-in mode wire feed control provides excellent arc starting characteristics for automatic GMA welding, regardless of the power supply type or mode. In the area of residual stresses, measurements show that the highest residual stresses were introduced in both conventional and pulsed GMA welded joints. These residual stresses, however, did not cause excessive distortion or lower fatigue strengths in the GMAW panels.

6.2.2 Pulsed GMAW - Pulsed GMAW was one of the three fillet welding processes chosen for complete testing. Next to conventional GMAW process, the pulsed GMAW showed the best combination of economics, static and fatigue strength, with low distortion and good corrosion resistance. The high-frequency pulsed GMAW process also provided a weld metal grain refinement over conventional GMAW. The improved grain refinement, however, provided no increase in mechanical properties compared with the conventional GMAW.

6.2.3 High-Frequency Resistance Welding - The high-frequency resistance welding was the third process chosen, based on its static and fatigue strength, for complete fillet weld joint evaluation. Out-of-plane distortion was considerably higher in the high-frequency resistance welded panel because of the preheating that had to be done in order to complete a sound well (See paragraph 2.1.3.3). High-frequency resistance welding can produce aluminum fillet joints that are equivalent in static and fatigue strength to conventional GMAW. Different "T" stiffener designs could improve the heat balance and distortion problem.

6.2.4 Explosion Welding - The explosion weldments produced were disappointing based on the original projections of what this process could do. It is true that the contract provides a great deal of data on tooling schemes that should not be used on aluminum, however, the final joints produced by the explosion welding process are not adequate for structural applications, because of low static and fatigue strengths and large out-of-plane distortions. Redesign of the extruded "T" stiffener to take into account the particular tooling and welding considerations for explosion joining will improve the quality of the explosion joint (See paragraph 5.1.1.4.2).

6.2.5 In-Chamber Electron Beam Weldtrusion - The in-chamber electron beam weldtrusion had the lowest heat input per inch of weld. This resulted in the least shrinkage and lowest angular distortion of any of the fillet weld processes. E.B. weldtrusion panels had by far the lowest static and fatigue strength. Redesign of the "T" stiffener to incorporate a wide base at the bottom of the web of the "T" will provide a wider weld which can increase the static and fatigue strength of this joint (See paragraph 5.1.1.5.2). It was determined that no additional filler wire is necessary on the electron beam weldtrusion process. However, close control of the vacuum and power levels are necessary to avoid cracking of the weld.

6.3 Butt Welds - The three butt weld processes evaluated appeared to be approximately equal in their static and fatigue strengths. When applying these butt welding processes to in-shipyard fabrication, it appears that the high cost of the sliding seal electron beam welding equipment, at this time, cannot provide enough increased productivity or as-welded properties to justify its expense. Here, again, the conventional GMAW process is the most practical selection for standard in-shipyard fabrication of butt welds, today and in the near future.

6.3.1 GMAW - There does not appear to be an advantage in reducing distortion between single-sided GMA butt welds vs. two-sided GMA butt welds in 3/16" thick material.

6.3.2 Plasma-GMAW Process - The contract has demonstrated that acceptable plasma GMA welds can be produced for butt welding aluminum. Because it appears this process has not been refined for thin gauge welding of aluminum, additional work could generate much lower heat inputs and, therefore, lower distortion. At this time, plasma-GMA welding does not provide any unique property to aluminum butt welding which would make it more advantageous than conventional GMAW.

6.3.3 Sliding Seal Electron Beam - The sliding seal electron beam welds made in France were manufactured using significantly lower heat input per inch of weld than the other processes. This reduced heat input for the sliding seal EB produced the minimum distortion obtained on all butt welded panels produced. Static strength of sliding seal electron beam butt welds tested in this investigation were comparable to parent metal properties. Except for corrosion fatigue strength, S.S.E.B. butt welds exhibited the highest joint structural performance. The problems of equipment cost and joint fit-up were significant enough to offset the excellent structural performance of the S.S.E.B. welded joints and rank S.S.E.B. below GMAW in overall performance.

TABLE 6-1
ECONOMIC AND PERFORMANCE RATING OF FILLET AND BUTT WELDING PROCESSES

Category	Panel Shop Fabrication (Fillet Weld)											In-Shipyard Fabrication (Butt Welds)						
		GMAW		Pulsed GMAW		H. F. Res.		Explosion Weld		In chamber E.B. Trusion			GMAW		Plasma GMAW		Sliding Seal E.B.	
	Weight	Rating	Points	Rating	Points	Rating	Points	Rating	Points	Rating	Points	Weight	Rating	Points	Rating	Points	Rating	Points
Weld. Equip. Cost	2	5	10	4	8	2	4	3	6	1	2	4	5	20	3	12	1	4
Fixture & Tooling Cost	2	5	10	5	10	2	4	1	2	3	6	4	5	20	4	16	3	12
Weld Edge Prep.	2	5	10	5	10	3	6	1	2	2	4	4	5	20	4	16	1	4
Weld Consumables	3	3	9	3	9	5	15	1	3	4	12	3	3	9	1	3	5	15
Welder Training & Exp.	2	2	4	1	2	5	10	4	8	3	6	2	4	8	2	4	5	10
Set-up & Welding Time	5	4	20	4	20	5	25	1	5	2	10	3	4	12	2	6	5	15
Weld Soundness	3	5	15	5	15	4	12	3	9	5	15	3	5	15	5	15	5	15
Weld Strength	4		-		-		-		-		-	4	4	16	4	16	5	20
Static Beam Strength	4	5	20	5	20	5	20	2	8	1	4			-		-		-
Fatigue	3	5	15	5	15	4	12	(2)	6	(1)	3	3	5	15	5	15	5	15
Corrosion Fatigue	3	5	15	5	15	5	15	2	6	1	3	3	5	15	5	15	3	9
Residual Stress	1	3	3	3	3	4	3	1	7	5	5	1	3	3	3	3	5	5
Hardness	1	4	4	4	4	4	4	5	5	3	3	1	4	4	3	3	5	5
Distortion	4	4	16	4	16	2	10	2	8	5	20	5	3	15	2	10	5	25
Corrosion	4	5	20	5	20	4	16	5	20	5	20	4	5	20	5	20	5	20
Total Points			171		167		162		89		113			192		154		174

Note Rating values 1-5 (5 best performance or least cost)
Weight factor - 5 most important category.
( ) Test not made assume same relative performance as corrosion fatigue.

Section 7 - Recommendations

1 - Conventional GMAW is clearly the best process for all types of aluminum welding for ship construction (Table 6-1). The majority of funds available for aluminum welding R&D should concentrate on improving GMAW welding economics, welder performance, and joint strength.

2 - Sliding seal electron beam butt welds provided static strength comparable to those of the parent metal. This, coupled with the S.S. electron beam overall performance, should justify additional research and development on the process in order to improve its economics and joint fit-up tolerance. In addition, further study should be made to investigate procedures to improve the root of the sliding seal electron beam weld to improve its corrosion fatigue properties.

3 - The S.S. electron beam static performance shows the potential for increasing butt weld strength in other welding processes by decreasing the width of the weld. Research and development funds should be spent in an attempt to improve GMAW weld strength in this manner.

4 - The fatigue strength of all the welding processes were limited by surface roughness, geometry of the weld, and porosity. GMAW techniques should be developed to minimize sources of fatigue crack initiation, thereby increasing the fatigue strength of GMAW welded joints.

5 - Hardness and residual stresses studies were not utilized to any large extent in this evaluation, and could be eliminated in future evaluations of this type. Actual distortion and strength measurements were used to better define the effects of welding on joint performance. More fundamental studies, beyond the scope of this contract, could be undertaken to determine the effect of residual stress on buckling and fracture characteristics of aluminum structures.

6 - Plasma GMAW welding is in its infancy and surveillance of its technology should continue in the hopes that some breakthroughs may be possible. U.S. Navy funding of additional work is not justified.

7 - High-frequency resistance welding holds future potential for producing large volumes of stiffened panels competitively with GMAW. A small program should be funded to investigate the performance of high-frequency resistance welds utilizing a modified stiffener, such as described in Figure 5-1.

8 - The subsize fillet welds used in the GMAW and pulsed GMAW segment of this contract performed extremely well and subsequent data has shown that they can substantially reduce distortion. Those individuals responsible for Navy design specifications should analyze the data presented in this report and determine where and how the subsize fillets can be used.

9 - Static and fatigue tests in the transverse direction should be made during future programs evaluating aluminum welds, because some of the loading on ship structures is in this direction. High-frequency resistance and electron beam weldtrusion specimens may not have performed as well in the transverse tests, particularly those that bend the sheet in the area of the weld.

APPENDIX - A - ULTRASONIC INSPECTION OF FILLET WELDS

A.1 OBJECTIVE - The object of this work is covered in the section of the proposal for this contract and is as follows:

A.2 "ULTRASONIC INSPECTION - Ultrasonic inspection of welds is well established as a standard reliable weld testing technique and is performed either in the immersion or contact mode. However, the relatively thin sections used in these "Tee" weldments will make ultrasonic inspection very difficult. In addition, the immersion technique requires that the part be submerged in water for testing a practice which could not be used when welding large modules. Consequently, the contact testing method is proposed as shown in Fig. A-1.

The ultrasonic inspection of welds will be attempted in accordance with the following program. Several weld standards will be produced which contain various degrees of incomplete fusion in the fillet weld area. Twin contact transducers, which provide good resolution of discontinuities near the part surface will be evaluated by employing the standards with known discontinuities. The transducer with the best sensitivity and producing the most readily interpreted screen presentation will then be employed in testing weld specimens. Where discontinuities are encountered, they will be marked on the parts and, if possible, examined metallographically to identify the source of the ultrasonic indication."

A.3 MATERIAL - Tee stiffened sections made by the following welding techniques were ultrasonically tested for percent penetration.

(1) Conventional GMA Welding
(2) High Frequency Pulsed GMA Welding
(3) High Frequency Resistance Welding
(4) Electron Beam Welding
(5) Explosive Welding

A.4 WELD STANDARDS - Five - 8 inch long standards were supplied by the Joining Division. These were welded using 3/16" 5456-H116 sheet and 2" x 3" 5456-H111 "T" extrusions. The standards were made with 0, 10, 50, 75 and 100% penetration. Figure A-2 illustrates the typical weld standards produced.

A.5 TRANSDUCER EVALUATION - Two dual-contact transducers were employed for evaluation with respect to sensitivity, interpretation of screen pattern, and ease of manipulation. The specifications for these units are as follows:

No.	Description
1	Automation Industries Dual-Contact Longitudinal Beam Transducer, Type SRZ-Z, 10 MHz, .125" x .250", Style 57A9261(U).

2 Branson Dual-Contact Longitudinal Beam Transducer, Type Z-103-FD, 5 MHz, .250" Dia.

In the initial feasibility evaluation, it was determined that both transducers easily detected lack of fusion at relatively low instrument gain settings using an Autiac 1203 (Alcoa Design) instrument and the contact mode illustrated in Fig. A-1. Mineral oil was used as a couplant in this test. A section of welded Tee section representing a full penetration weld was tested using both transducers and a test instrument standardization of 1.5 inch indication from a 3-0025 reference block. In scanning the weld, several indications were detected and one of these areas, as well as the area indicating full penetration, was examined metallographically. Fig. A-2 shows a macrograph of the full penetration area without an indication and the weld area in the position showing an indication. Figure A-4 illustrates the indication at a higher magnification.

Ultrasonic reflectograms obtained for this sample are presented in Figs. A-5 and A-6. Figure A-5(a) illustrates the pattern obtained from a 3/64" dia. flat bottom hole in a Series "D" aluminum reference block at 1/4" metal distance and represents the standardization of the instrument for testing this specimen. Figure A-5(b) illustrates the screen pattern obtained when inspecting the 3/16" thick sheet only, which would be very similar to the screen pattern observed for no penetration.

Fig. A-6(a) shows the indication noted from the unfused area in the specimen (measured at approximately 55% penetration) while Fig. A-6(b) shows the screen pattern in an area of 100% penetration.

Following the initial evaluation, the prepared weld standards representing 0 to 100% penetration were measured using each transducer. The standardization sensitivity was selected at 1.5 in. on a 5-0025 reference block to keep the indication of the 10% standard on screen and the unwelded plate indication in saturation. Table A-1 presents the data developed in this test. As can be seen, an accurate quantitative measurement of degree of fusion could not be obtained, but a useful correlation between penetration and ultrasonic indications is evident.

It was noted during the tests that the 5 MHz transducer was hard to hold due to its small size; consequently, the 10 MHz transducer was selected for subsequent testing. This transducer was also pulsed at 5 MHz since a lower gain and sharper screen presentation were evident at this pulse frequency. Measurement of the effective beam width of the 10 MHz transducer showed it to be .187" in either direction at 1/4" metal distance. This is near an optimum size to detect lack of fusion in a welded 1/8" thick Tee section.

A.6 TESTING OF WELDED SPECIMENS - Similar results were obtained on the weld standards when using a commercial Automation Industries UM721 ultrasonic test instrument. This instrument was used for all weld specimen tests since it was more readily available for use. Figure A-7 is a schematic of the 10 MHz transducer position used in all weld sample testing while Fig. A-8 is a photograph of the general testing set-up as shown on one of the weld penetration standards. Reflectograms in Fig. A-9 illustrate the screen patterns obtained on the UM721, and Table A-2 presents the standardization of the test and the relationship of percent penetration to ultrasonic indications. These data are plotted in Fig. A-10.

The welded samples were generally 48 inches in length and testing was performed at intervals of 6 inches. Values of the maximum ultrasonic indication obtained at each station were recorded and identified on the specimen.

A.7 RESULTS & DISCUSSION - Tables A-3 through A-6 list the individual measured ultrasonic indications for each type of weld samples. Stations from which metallographic specimens were taken for correlation with ultrasonic results are marked with an asterisk. Table A-8 summarizes the results of the metallographic-ultrasonic correlation.

A.7.1 CONVENTIONAL GMA WELDS - Evaluation of the results in Table A-3 shows that in general the ultrasonic values are fairly constant along the length of the weld. There were several stations where variations existed, and some of these were selected for metallographic tests where the test location did not interfere with other planned fatigue tests. Ultrasonic vs. % penetration results in Table A-8 for this type of weld showed correlation in 2 out of 3 samples. Micrographs of these specimens are presented in Figs. A-11 to A-13. The unwelded area is reported in inches, and the ultrasonic indication height in inches is reported as USI.

There is a slight ridge produced on the sheet side of the specimen which sometimes results in a rocking action of the transducer. While this would normally be expected to produce a lower indication, it may have been the reason for lack of correlation since the transducer was manipulated for maximum indication while against the guide. Localized variation of the % penetration or variation in oil couplant may also have been the cause of the lack of 100 precent correlation.

A.7.2 HIGH FREQUENCY PULSED GMA WELDS - Table A-4 shows variation along the length of these welds and between welds was very low in most cases. Sample 7 in this graph had lower values, indicating higher % penetration, and was selected for metallographic examination. Table A-8 results for this weld type show that only 1 out of 3 values of % penetration correlate with the ultrasonic results. Figures A-14 to A-16 show micrographs for these samples. The samples also had a slight ridge on the sheet side, and this fact plus localized variation in the weld may be the explanation for the lack of correlation.

A.7.3 HIGH FREQUENCY RESISTANCE WELDS - These welds showed minor variation in ultrasonic indication along the welds, see Table A-5, and some larger variation between weld specimens. However, it was not possible to metallographically examine specimens representing the full range of ultrasonic indications due to the demands for mechanical test speciments. The results of those examined are shown in Table A-8 and then micrographs in Figs. A-17 to A-19. Only 1 out of 3 correlations were found. This is probably due to the fact that there is no fillet in these welds, and the unbonded region is at the edge of the 1/8" thick plate. A better correlation could be established if standards of varying penetrations were produced from high frequency resistance welds.

A.7.4 ELECTRON BEAM WELDS - The welded samples in this category could not be ultrasonically tested in the as-welded condition due to the fact that there was a weld bead present which did not allow full transducer contact with the plate side. This condition can be seen in Fig. A-20. Three 8" long specimens were prepared by machining the bead away and providing a flat surface for testing. Results of this test are shown in Table A-6, and the correlation results in Table A-8. There was correlation in 2 out of 3 cases even though, as in the case of the high frequency resistance welds, there is no fillet formed in this type of weld.

A.7.5 EXPLOSION WELDS - Four explosion weld samples were submitted for tests. These as-welded "T" sections were severely distorted. The plate flange was not flat, and a ridge was formed on the plate opposite the web. An additional .064" shim for explosive welding was welded to the web side of the plate and could not be removed. Ultrasonic readings were taken since a readable indication was possible. A summary of these results are shown in Table A-7 and correlation with metallographic tests are listed in Table A-8. No correlation was obtained in this case and is due to the combination of poor transducer contact resulting from the warped samples. Even sample 952-4 which had 2.4 in. indication, representing 10-25% penetration, proved to be unwelded when cut for metallographic examination. Figures A-21 and A-22 illustrate the metallographic structure in welded areas and show a sound weld.

A.8 CONCLUSIONS - Contact testing of fillet welds using a twin search unit is possible, but the accuracy of determining the percent of penetration is much lower than would be desirable. The accuracy is mainly affected by the height of the ridge formed on the plate side of the specimen, and in the case of the electron beam weld prevented a test. It appears that the test would have value in detecting welds of 25% penetration or higher when the flatness of the plate opposite the web can be controlled.

TABLE A-1

ULTRASONIC TEST RESULTS ON SAMPLES SHOWING VARIOUS DEGREES OF FILLET WELD PENETRATION

A. Search Unit - 5 MHz - .250" Dia. Dual

Autiac Gain - #3 Attenuator = 7.0, Receiver Gain = .4

Standardization - 1.5 In. Indication on #5-0025 Reference Block

Sample	Indication Height, In.
3/16" Sheet Only	Saturated, >4.
10% Penetration	3.5-4.
50% Penetration	2.5-3.
75% Penetration	1.5-2.
100% Penetration	0

B. Search Unit - 10 MHz - 1/8 x 1/4 Rectangular Dual (pulsed at 5 MHz)

Autiac Gain - #3 Attenuator = 7.0, Receiver Gain = .7

Standardization - 1.5 In. Indication on #5-0025 Reference Block

Sample	Indication Height, In.
3/16" Sheet Only	Saturated, >4.
10% Penetration	3.0-3.5
50% Penetration	2.5-3.0
75% Penetration	2.0-2.5
100% Penetration	0

TABLE A-2

STANDARDIZATION FOR FILLET WELD
TESTING OF VARIOUS WELDING METHODS

Search Unit - 10 MHz - 1/8 x 1/4 Rectangular Dual
(pulsed at 5 MHz) S.U. SRZ #57A9261 AI

UM721 Gain - 2.5 x 10 (typical)

Standardization - 2.0 In. Indication from #8-0025 Reference Block

Sample	Indication Height, Ins.
3/16" Sheet Only	Saturated, 2nd Br 1.8 In.
10% Penetration	2.0-2.5
50% Penetration	1.0-2.0
75% Penetration	.5-1.0
100% Penetration	0- .2

TABLE A-3

SUMMARY OF ULTRASONIC INDICATIONS ON SPECIMENS OF CONVENTIONAL GMAW
S. NO. 420914 - UM721 - VALUES ARE MAXIMUMS (INS.)

STATION		1	2	3	4	5	6	7	
DISTANCE FROM END - INCHES	0	6	12	18	24	30	36	42	48
SPECIMEN									
420914-1		2.5	2.8	2.6	2.8	2.8	2.6	2.6	
-2		1.8	2.8	2.4	2.4	2.6	2.4	2.2	
-3		2.4	2.6	2.8	2.4	2.6	2.8	2.8	
-4		2.4	1.8	2.5	2.4	2.4	1.5	.7*	
-5		2.4	2.3*	2.4	2.4	2.4	2.6	2.0	
-6		2.2	2.2	2.8	2.8	2.8	2.7	2.6	
-7		1.8	2.4	2.7	2.6	2.7	2.5	2.4	
-8		2.0	1.3	1.6	1.6	2.4	2.0	2.0	
-9		2.4	2.4	2.6	2.7	2.2	1.8	2.1	
-10		2.5	2.6	2.8	2.3	2.6	2.6	2.2	
-11		2.3	2.3	2.4	2.5	2.3	2.4	2.3	
-12		2.5	2.3	2.5	2.5	2.4	2.6	2.2	
-13		2.3	1.8	2.2	2.5	2.4	2.7	2.5*	
-22		1.8	1.9	1.9	1.9	1.8	1.8	1.8	

*Metallographic Specimens.

TABLE A-4

SUMMARY OF ULTRASONIC INDICATIONS ON SPECIMENS OF HIGH FREQUENCY PULSED GMAW

S. NO. 420910 - UM721 - VALUES ARE MAXIMUMS (INS.)

STATION		1	2	3	4	5	6	7	
DISTANCE FROM END - INCHES	0	6	12	18	24	30	36	42	48
SPECIMEN									
420910-1		2.4	2.4*	2.6	2.2	2.4	2.2	2.2	
-2		2.4	2.2	2.0	2.0	2.0	2.3	2.2	
-3		2.5	2.5	2.4	2.6	2.4	2.4	2.4	
-4		1.4	1.4	1.3	1.3	2.3	2.0	1.4	
-5		1.8	1.9	2.0	1.8	2.0	1.2	1.6	
-6		2.1	2.1	2.2	2.1	2.0	2.0	2.0	
-7		1.7	1.5	1.5	1.6	1.8	1.8	1.6*	
-8		2.2	2.2	2.2	2.0	2.1	2.2	2.3*	
-9		2.4	2.2	2.0	1.4	2.2	2.1	2.1	
-10		2.0	2.1	2.1	2.0	2.1	2.0	1.9	
-11		2.0	2.0	2.1	2.2	2.3	2.2	2.2	
-12		2.1	2.1	2.2	2.1	2.2	2.2	2.2	

*Metallographic Specimens.

TABLE A-5

SUMMARY OF ULTRASONIC INDICATIONS ON SPECIMENS OF HIGH FREQUENCY RESISTANCE WELDS

S. NO. 420914, 15, AND 16 - UM721 - VALUES ARE MAXIMUMS (INS.)

STATION		1	2	3	4	5	6	7	
DISTANCE FROM END - INCHES	0	6	12	18	24	30	36	42	48
SPECIMEN									
(1) 420916-1		1.3	1.4	1.2	.8	1.3*			
-3A		.9	1.1	1.0	.9	1.1			
-3B		1.2	1.1	.9	.8	.9			
-3C		1.1	1.2	1.1	1.0	1.1*			
-7A		1.2	1.2	.9	1.0	1.0			
-7B		1.0	1.0	1.2	1.1	1.2			
-9A		1.1	1.0	1.1	.9	1.0			
-9B		1.0	1.2	1.0	1.2	1.1			
-10		1.2	1.1	1.2	1.2	1.1*			
-6		1.1	.9	.6	.7	.5			
-8		1.2	.6	.6	.6	.5			
-11A		.9	.9	1.0	.9	.8			
420914-22		1.8	1.9	1.9	1.9	1.8	1.8	1.8	
420915-1		.8	1.0	1.1	1.2	1.2	1.1	1.2	
-2		1.8	2.0	2.0	2.0	2.0	2.1	2.1	

(1) These samples warped badly in longitudinal direction and were 36" long. Slight ridge over weld on plate side.

*Metallographic Specimens.

TABLE A-6

SUMMARY OF ULTRASONIC INDICATIONS
ON SPECIMENS OF ELECTRON BEAM WELDTRUSION

S. NO. 420913 - UM721 - VALUES ARE MAXIMUMS (INS.)

SPECIMEN	INDICATION, INS.
420913-4	1.5
420913-5	1.0
420913-8	.9

NOTE: As-welded specimens could not be tested due to ridge formed on plate side opposite welded web. Above data obtained after machining away ridge to provide flat surface to contact test.

TABLE A-7

SUMMARY OF ULTRASONIC INDICATIONS ON SPECIMENS OF EXPLOSION WELDS

S. NO. 420952 - UM721 - VALUES ARE MAXIMUMS (INS.)

STATION		1	2	3	4	5	6	7	
DISTANCE FROM END - INCHES	0	6	12	18	24	30	36	42	48
SPECIMEN									
420952-1	1.1*	1.0	1.0	.4	.6	.8	.8	.5	1.8
-2	Sat.	.4	.5	.2	.4	.4	.4	.4	1.0
-3	1.0	.6	.4	.4	.6	.7	.6	.6	2.0
-4	2.4*	1.1	.8	.5*	.5	.5	.8	.8	2.4

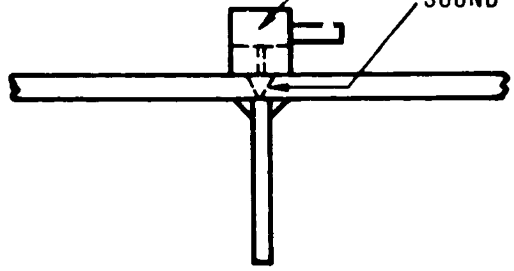
*Metallographic Specimens.

NOTE: As-welded specimens were severely distorted. Plate flange was not flat and ridge was formed on plate opposite web. Data was obtained even when this condition existed since a readable indication was possible.

TABLE A-8

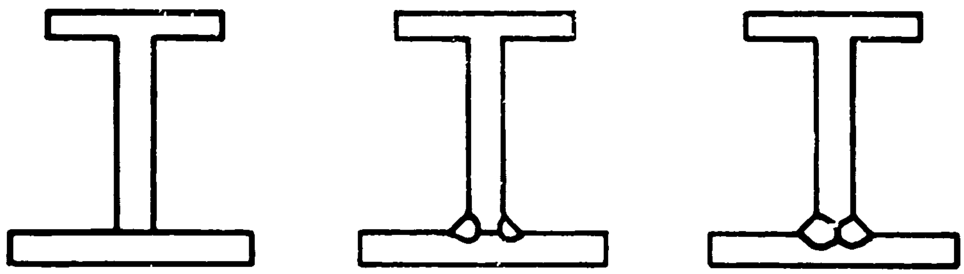
SUMMARY OF METALLOGRAPHIC EXAMINATION CORRELATION WITH ULTRASONIC INDICATIONS

WELD TYPE	SAMPLE	LAND - INCHES	SONIC IND. - INS.	ACTUAL % PENETRATION	ESTIMATED % PENETRATION	CORRELATION	STATION
Conventional GMA	914-4	.027	.7	78	65-80	Yes	7
	914-5	.063	2.3	50	10-30	No	2
	914-13	.094	2.5	25	5-25	Yes	7
High Frequency Pulsed GMA	910-1	.0608	2.4	52	10-25	No	2
	910-7	.054	1.6	57	25-60	Yes	7
	910-8	.0608	2.3	52	10-30	No	7
High Frequency Resistance	916-1	.026	1.3	79	35-65	No	5
	916-3	.054	1.1	57	45-70	Yes	5
	916-13	.018	1.1	85	45-70	No	5
Electron Beam (Machined)	913-4	.078	1.5	37	30-65	Yes	5
	913-5	.055	1.0	56	50-75	Yes	5
	913-8	.078	.9	37	55-80	No	5
Explosion Weld	952-1	.0135	1.1	90	45-70	No	0 (end)
	952-4	.125	2.4	0	10-25	No	0 (end)
	952-4	.006	.5	95	75-90	No	3



ULTRASONIC TEST METHOD

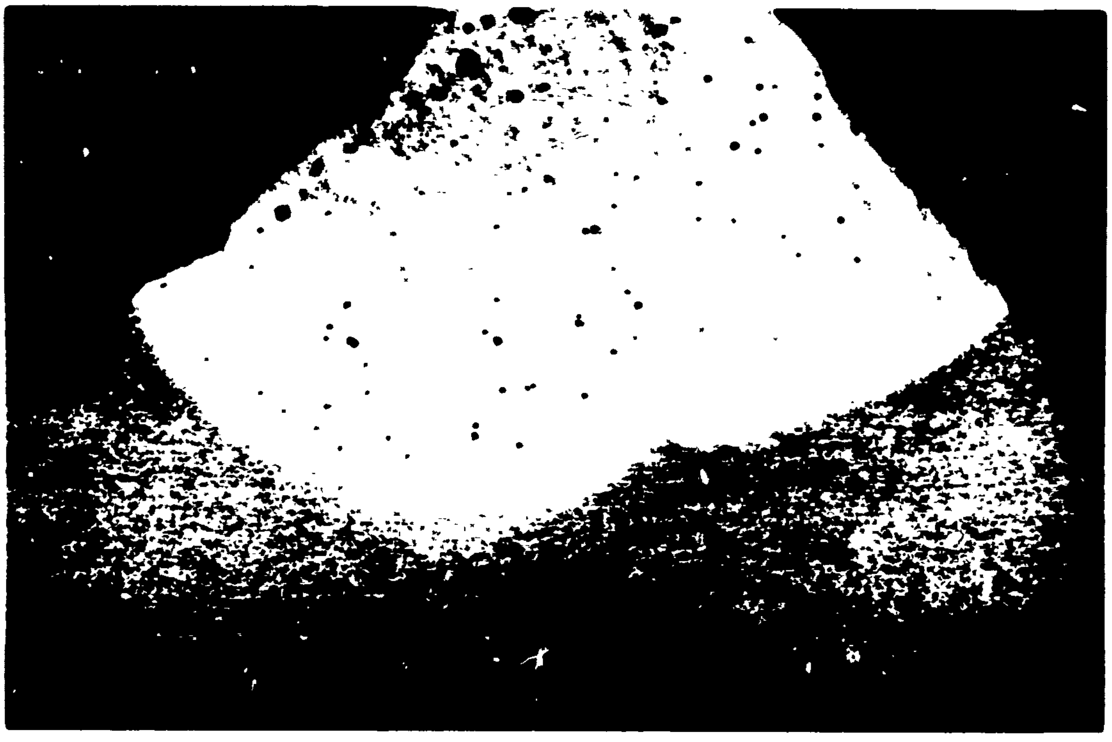
FIGURE A-1



TYPICAL ULTRASONIC WELD STANDARDS

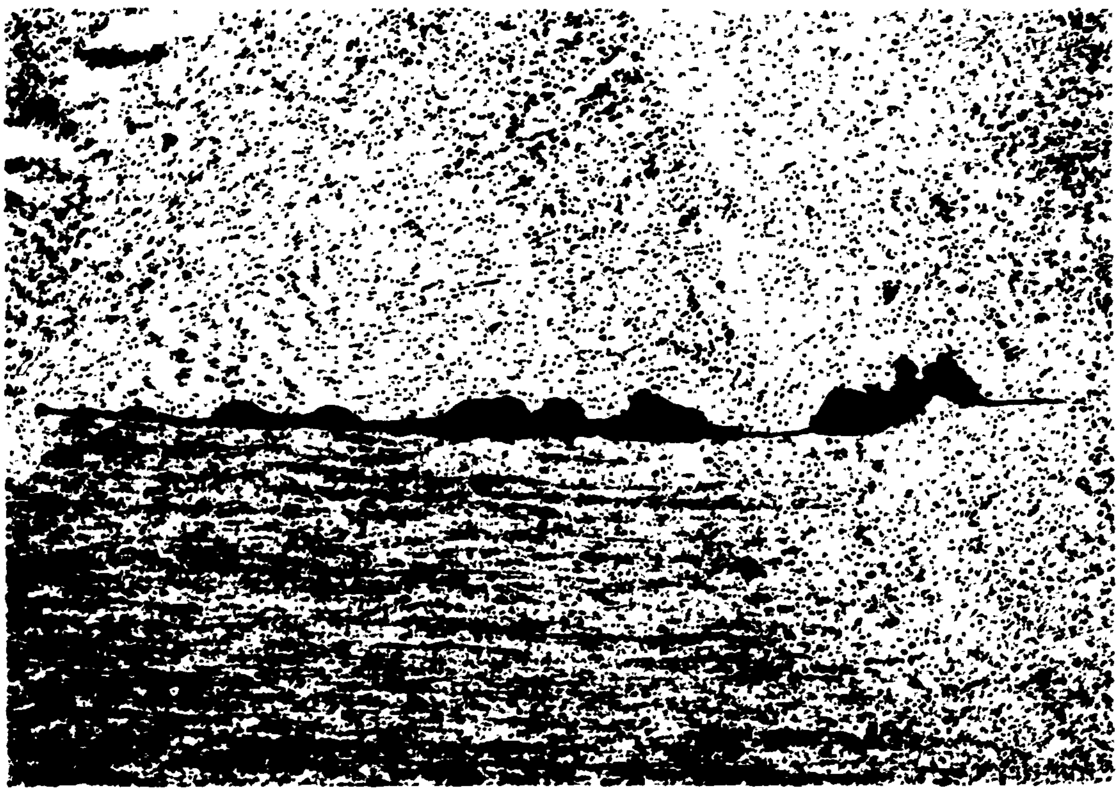
FIGURE A-2

CROSS-SECTION OF AREA SHOWING ULTRASONIC INDICATIONS
10X - KELLER'S ETCH
NEG. NO. 195172A SPEC. NO. 244322



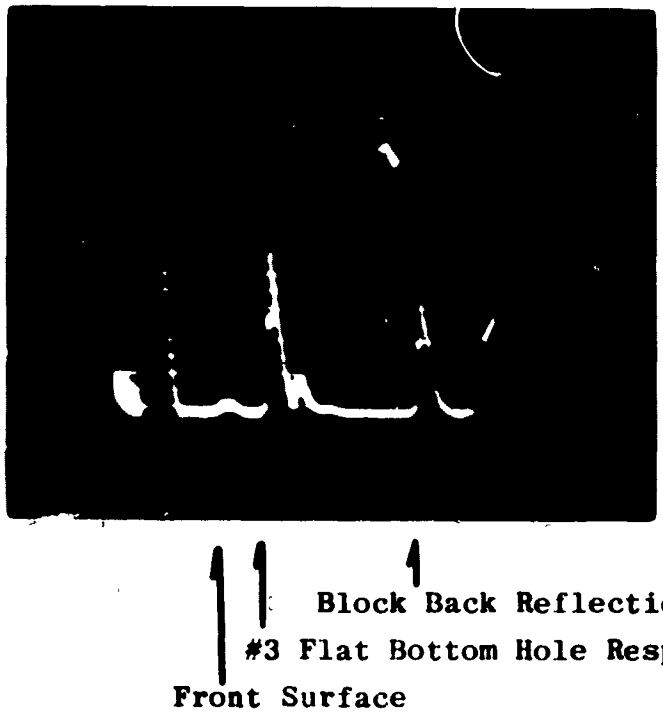
CROSS-SECTION OF AREA SHOWING NO ULTRASONIC INDICATIONS
10X - KELLER'S ETCH
NEG. NO. 195173A SPEC. NO. 244322

FIGURE A-3

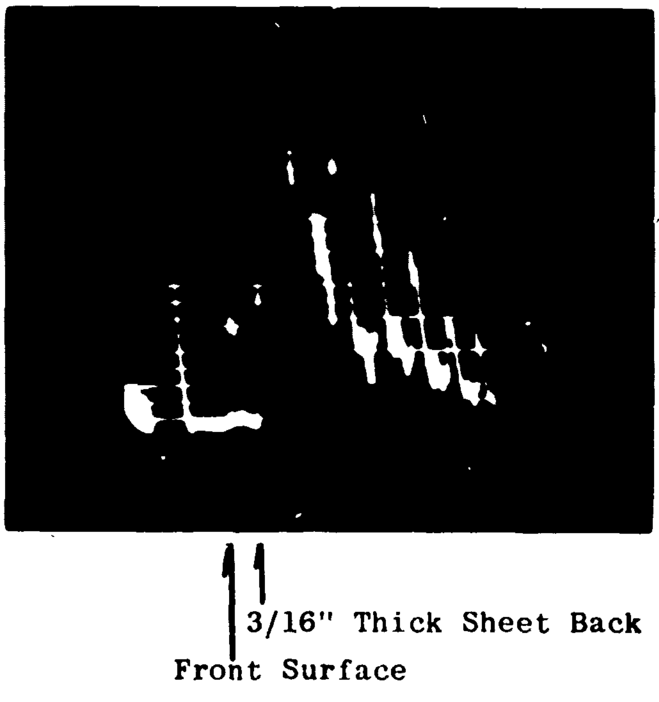


AREA SHOWING ULTRASONIC INDICATIONS
100X - KELLER'S ETCH
NEG. NO. 195171A SPEC. NO. 244322

FIGURE A-4

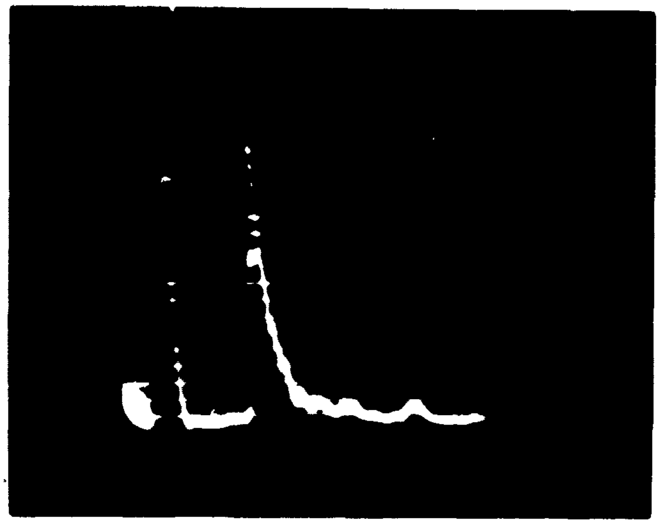


a. <u>Screen Pattern of Standardization 1.5" from #3.0025 Block</u>

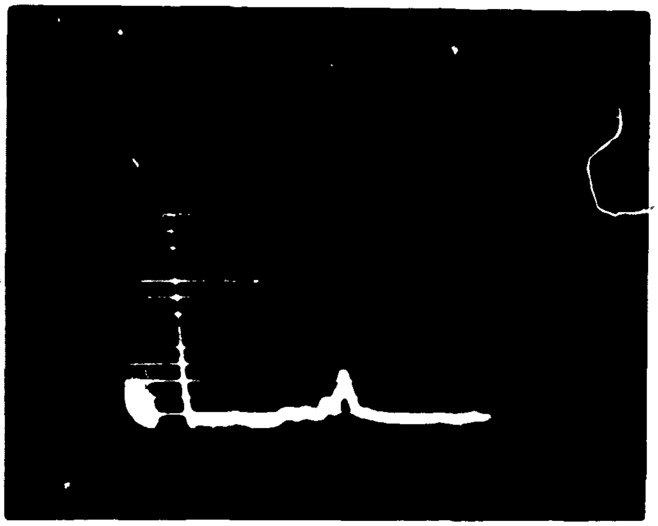


b. Screen Pattern of 3/16" Thick Sheet Only

FIGURE A-5

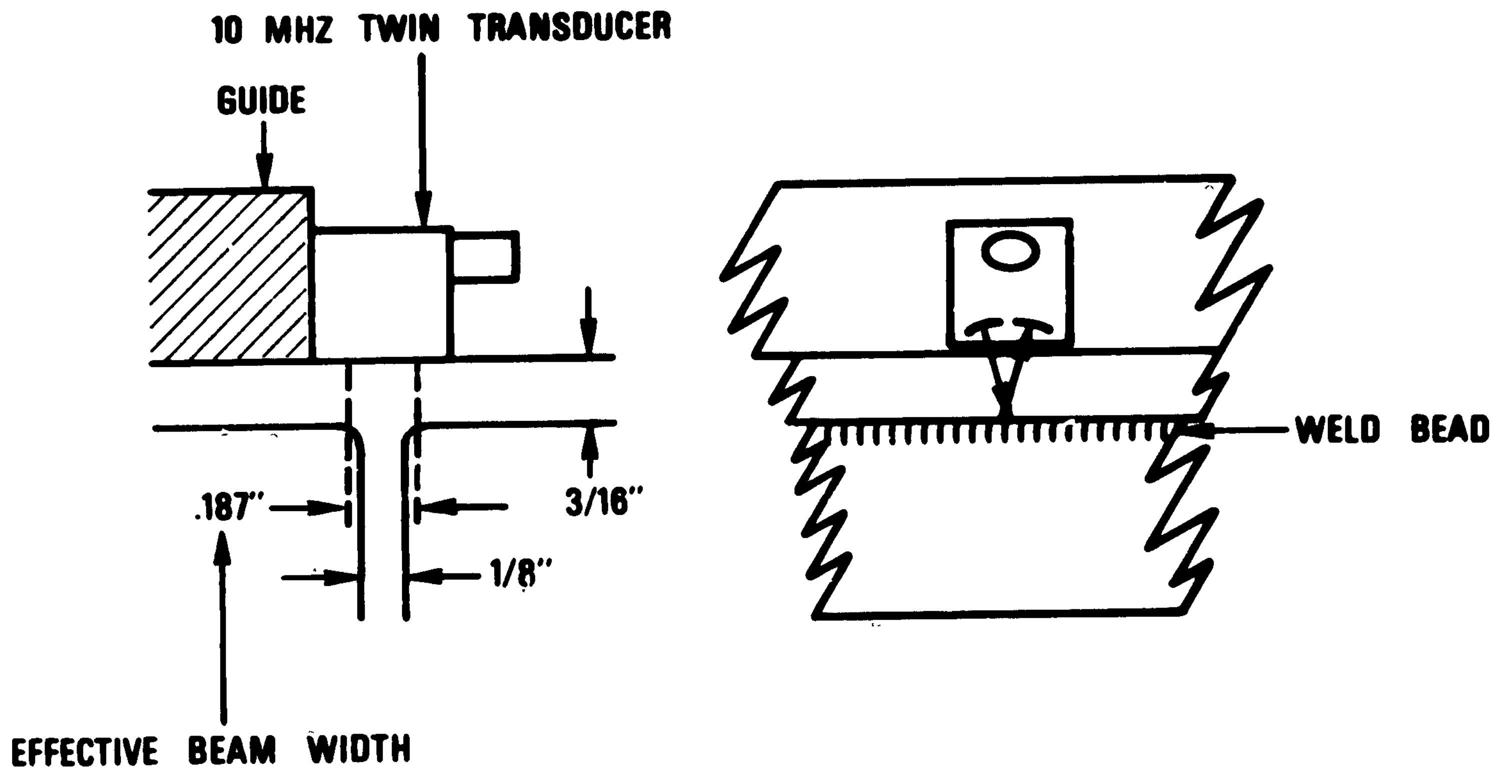


a. Screen Pattern of Area Showing Approximately 55% Penetration



b. Screen Pattern of Area Showing 100% Penetration

FIGURE A-6



SCHEMATIC DRAWING OF ULTRASONIC CONTACT TEST

FIGURE A-7

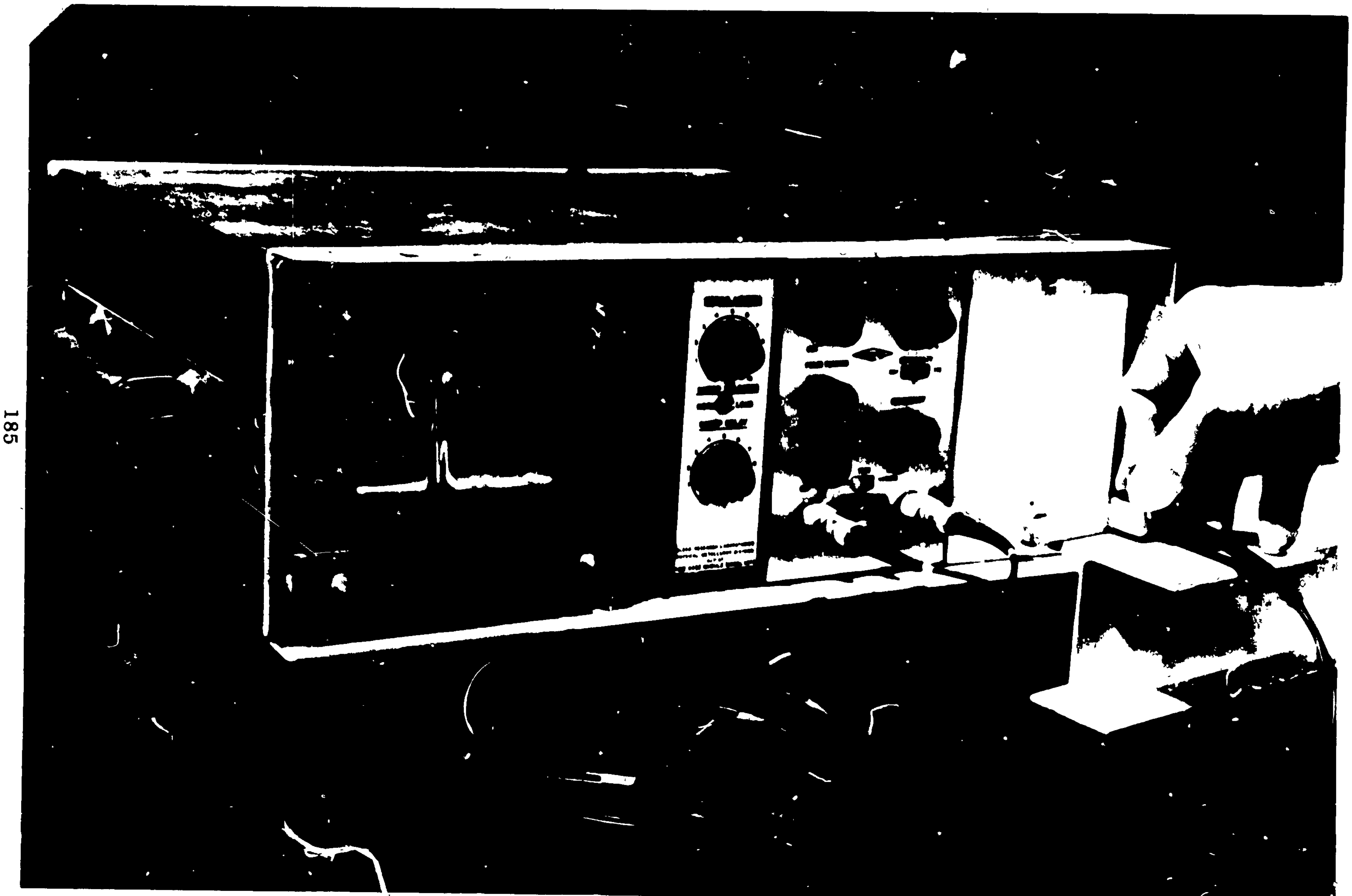
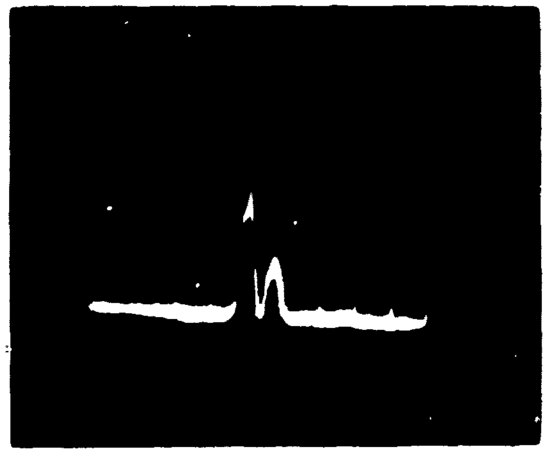


Figure A-8 - Photograph of Test Setup for Fillet Weld Test Employing UM721 and Twin Contact Search Unit

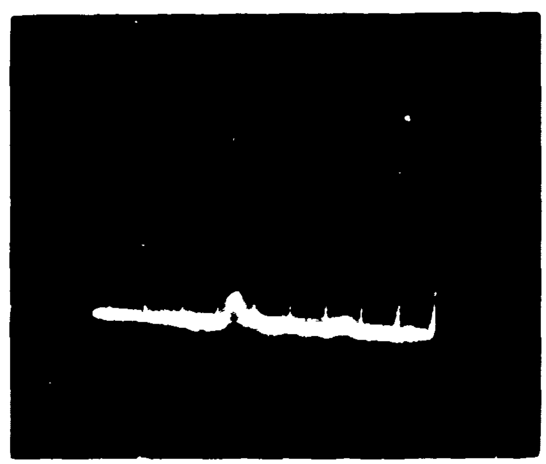
TYPICAL SCREEN PATTERNS OF STANDARDIZATION,
0%, 50%, AND 100% WELD PENETRATION

SAT. INDICATION FROM SHEET ONLY
i.e. - NO WELD - 0% PENETRATION
SECOND BACK REFLECTION ≅ 1.8 IN.



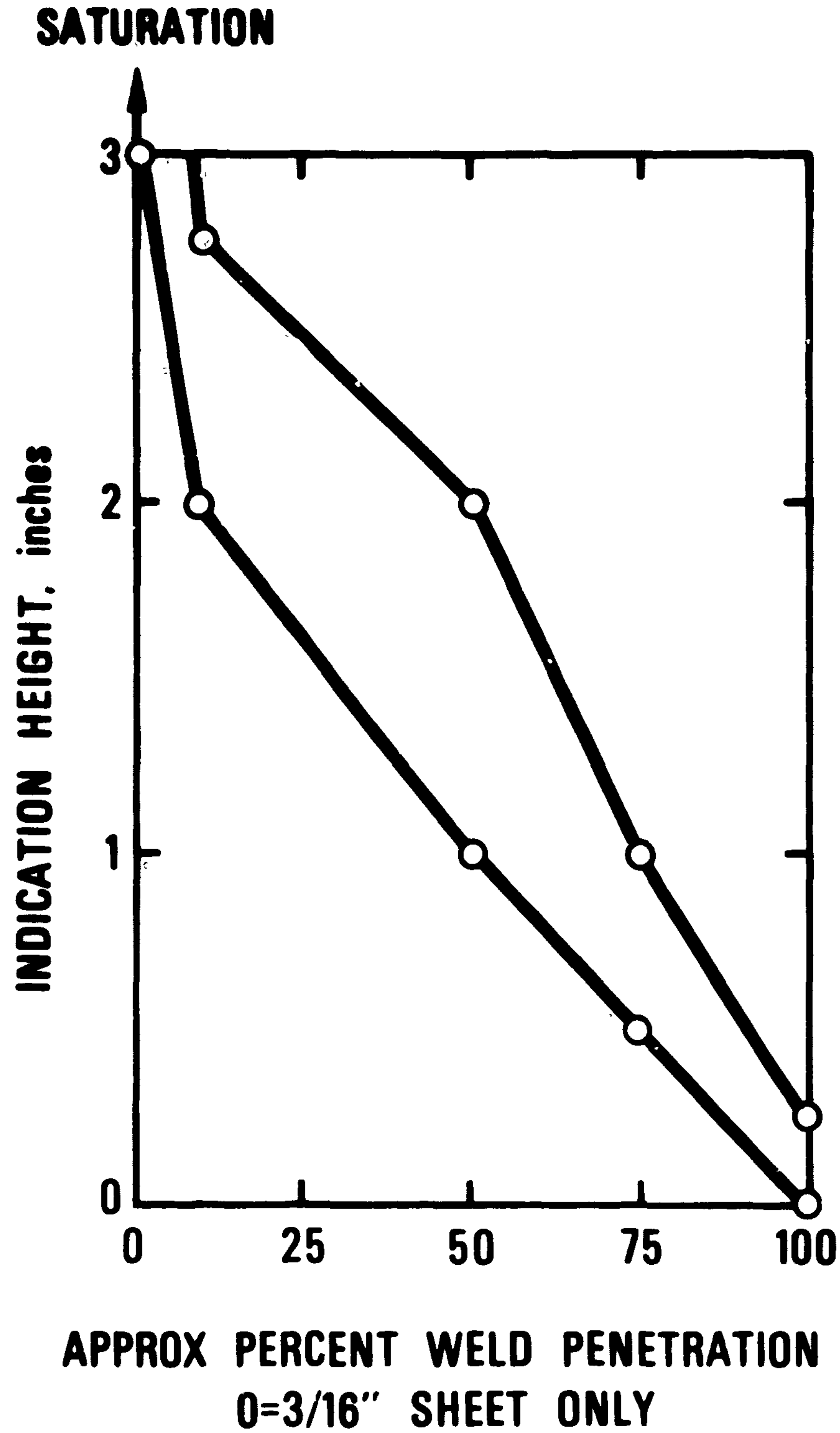
50% PENETRATION
1-2 IN. INDICATION

STANDARD 2 IN. INDICATION
FROM 8-0025 REFERENCE BLOCK



100% PENETRATION
0-.2 IN. INDICATION

FIGURE A-9



ULTRASONIC INDICATION vs APPROX % PENETRATION

FIGURE A-10

CONVENTIONAL GMAW

SPEC. No. 420914-4 NEG. NO. 196270A MAG. 15X ETCH: ELECTROPOLISH POLARIZED LIGHT

.027" LAND - USI = .7 IN. - % PENETRATION = 78%

STATION #7 EST. % PENETRATION = 65-80%

FIGURE A-11

CONVENTIONAL GMAW

SPEC. NO. 420914-5 NEG. NO. 196276A MAG 15X ETCH: ELECTROPOLISH POLARIZED LIGHT

.063" LAND - USI = 2.3 IN. - % PENETRATION = 50%

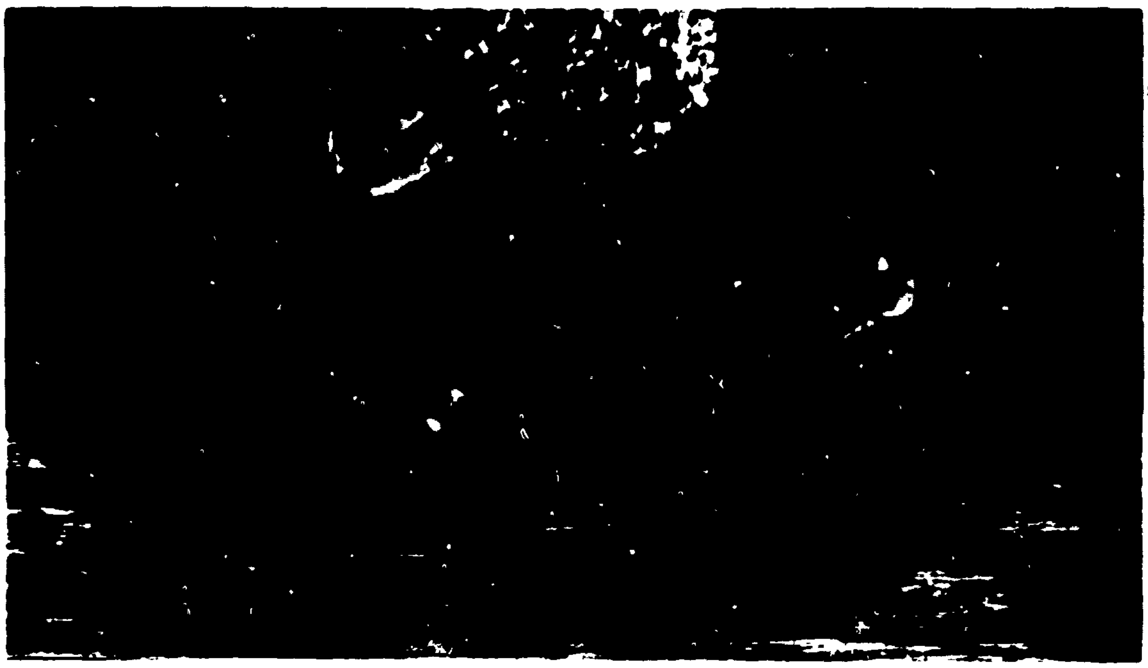
STATION #2 EST. % PENETRATION = 10-30%

FIGURE A-12

CONVENTIONAL GMAW
SP'.C. NO. 420914-13 NEG. NO. 196271A MAG 15X ETCH: ELECTROPOLISH
POLARIZED LIGHT
.094" LAND - USI = 2.5 IN. - % PENETRATION = 25%
STATION #7 EST. % PENETRATION = 5-25%
FIGURE A-13

HIGH FREQUENCY PULSED GMAW
SPEC. NO. 420910-1 NEG. NO. 196068A MAG. 15X ETCH: ELECTROPOLISH
POLARIZED LIGHT
.0608" LAND - USI = 2.4 IN. - % PENETRATION - 52%
STATION #2 EST. % PENETRATION = 10-25%
FIGURE A-14

HIGH FREQUENCY PULSED GMAW
SPEC. NO. 420910-7 NEG. NO. 196069A MAG. 15X ETCH: ELECTROPOLISH
POLARIZED LIGHT
.054" LAND - USI = 1.6 IN. - % PENETRATION = 57%
STATION #7 EST. % PENETRATION = 25-60%
FIGURE A-15



HIGH FREQUENCY PULSED GMAW
SPEC. NO. 420910-8 NEG. NO. 196070A MAG. 15X ETCH: ELECTROPOLISH
POLARIZED LIGHT
.0608" LAND - USI = 2.3 IN. - % PENETRATION = 52%
STATION #7 EST. % PENETRATION = 10-30%
FIGURE A-16

HIGH FREQUENCY RESISTANCE WELD
SPEC. NO. 420916-1 NEG. NO. 196273A MAG. 15X ETCH: ELECTROPOLISH
POLARIZED LIGHT
.026" LAND - USI = 1.3 IN. - % PENETRATION = 79%
STATION #5 EST. % PENETRATION = 35-65%
FIGURE A-17

HIGH FREQUENCY RESISTANCE WELD
SPEC. NO. 420916-3 NEG. NO. 196274A MAG. 15X ETCH: ELECTROPOLISH
POLARIZED LIGHT
.054" LAND - USI = 1.1 IN. - % PENETRATION - 57%
STATION #5 EST. % PENETRATION = 45-70%
FIGURE A-18

HIGH FREQUENCY RESISTANCE WELD
SPEC. NO. 420916-10 NEG. NO. 196277A MAG. 15X ETCH: ELECTROPOLISH POLARIZED LIGHT
.018" LAND - USI = 1.1 IN. - %PENETRATION = 85%
STATION #5 EST. % PENETRATION = 45-70%

FIGURE A-19

ELECTRON BEAM WELDTRUSION
SPEC. NO. 420919-5 NEG. NO. 196272A MAG. 15X ETCH: ELECTROPOLISH POLARIZED LIGHT

FIGURE A-20

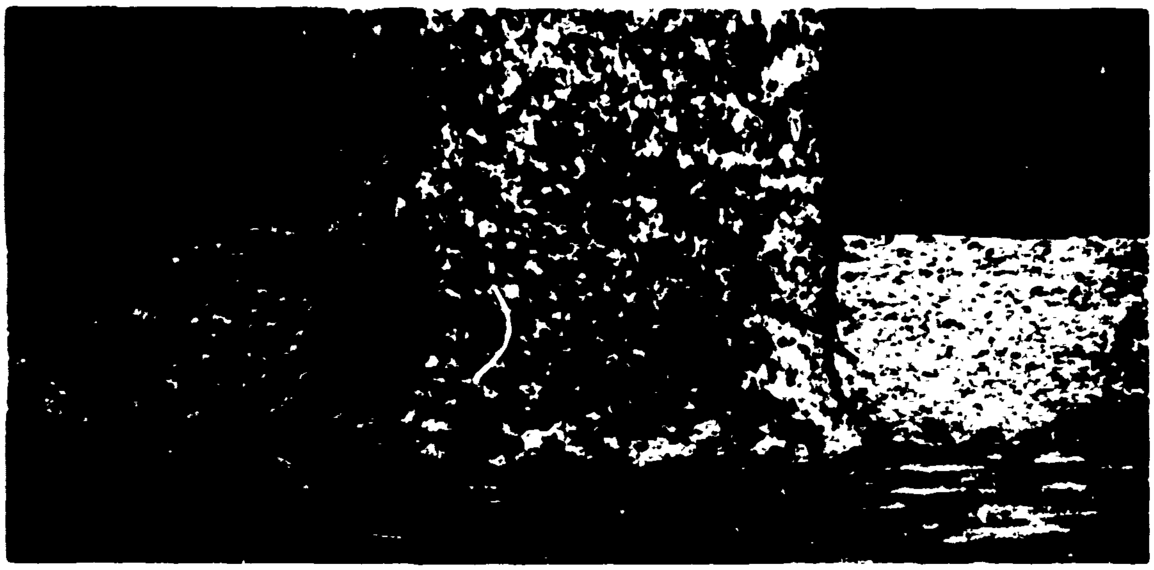
EXPLOSION WELD

SPEC. NO. 420952-1 NEG. NO. 197600A MAG. 20X ETCH: ELECTROPOLISH
POLARIZED LIGHT

GOOD GRAIN STRUCTURE IN EXPLOSIVE WELD

.0135" LAND - USI = 1.1 IN. - % PENETRATION = 90%

STATION #0 (END) EST. % PENETRATION = 45-70%



EXPLOSION WELD

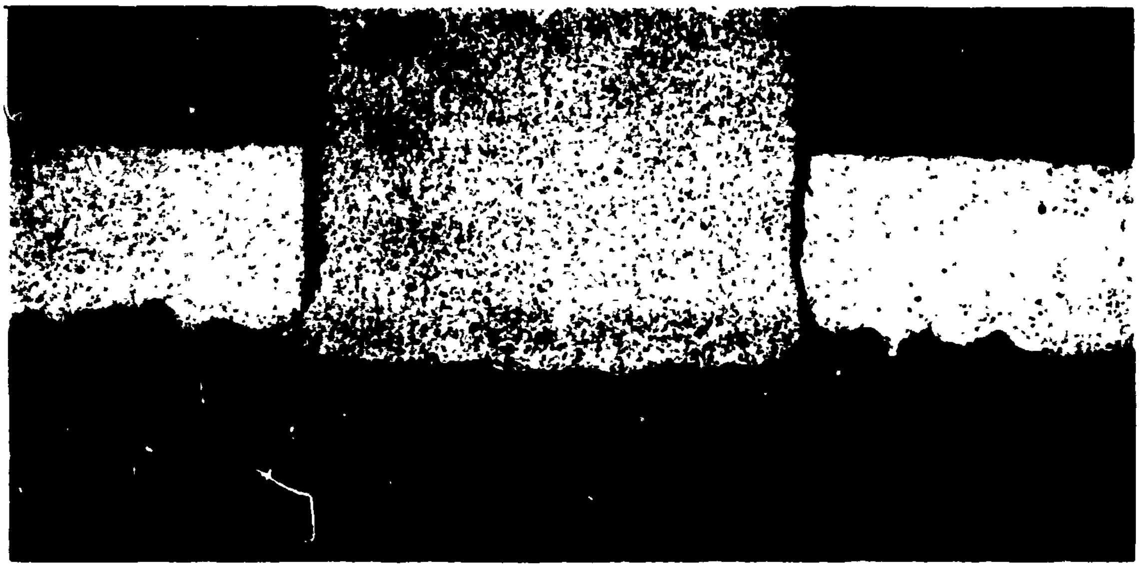
SPEC. NO. 420952-4 NEG. NO. 197601A MAG. 20X ETCH: ELECTROPOLISH
POLARIZED LIGHT

GOOD GRAIN STRUCTURE IN EXPLOSIVE WELD

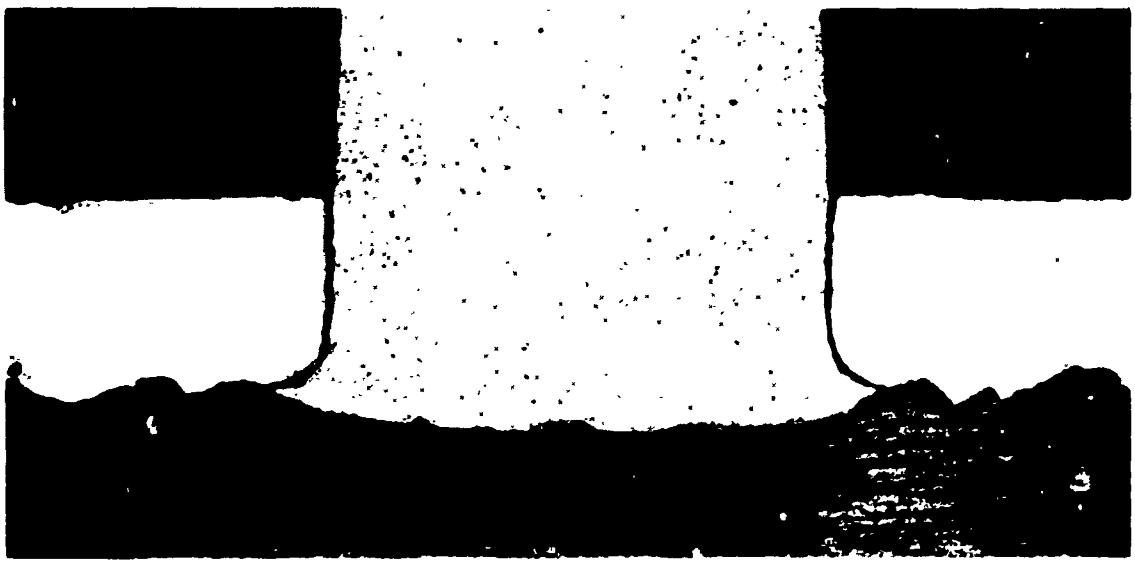
.006" LAND - USI = .5 IN. - % PENETRATION - 95%

STATION #3 EST. % PENETRATION = 75-90%

FIGURE A-21



EXPLOSION WELD
SPEC. NO. 420952-1 NEG. NO. 197602A MAG. 20X ETCH: ELECTROPOLISHED
NOT POLARIZED
SOUND WELD, SMALL UNFUSED ZONE
.0135" LAND - USI = 1.1 IN. - % PENETRATION = 90%
STATION #0 (END) EST. % PENETRATION = 45-70%



EXPLOSION WELD
SPEC. NO. 420952-4 NEG. NO. 197603A MAG. 20X ETCH: ELECTROPOLISHED
NOT POLARIZED
SOUND WELD, SMALL UNFUSED ZONE
.006" LAND - USI = .5 IN. - % PENETRATION = 95%
EST. % PENETRATION = 75-90%

FIGURE A-22